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DESERT OASES AS GEOHERITAGE-RICH AREAS: PRESENT KNOWLEDGE AND SUSTAINABILITY PERSPECTIVES IN THE WESTERN DESERT OF EGYPT AND BEYOND

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ABSTRACT. Contemporary progress in geological heritage (geoheritage) studies in deserts has allowed the identification of a new resource for sustainable development in oases. The field investigations and the bibliographical survey enable the identification of geoheritage-rich areas (GRA) in the Western Desert of Egypt and beyond. These GRAs reflect natural concentrations of peculiar geological and geomorphological features. Eight oasis-centered GRAs are outlined in the Western Desert of Egypt (Bahariya, Dakhla, Dungul, Faiyum, Farafra, Kharga, Kurkur, Siwa), and several GRAs of the same kind are found in North Africa (beyond Egypt), the Middle East, and western South America. The Egyptian GRAs often represented sedimentary, paleogeographical, and geomorphological features. It is established that these GRAs differ in geoheritage exploration and content, and the most comprehensive data are available for four oases of the Western Desert of Egypt (Bahariya, Farafra, Faiyum, and Siwa) and the Hingol area of Pakistan. It is argued that various sustainability aspects matter for the considered oases of the Western Desert of Egypt and can be linked to the United Nations Sustainable Development Goals. Utilization of geoheritage resources can contribute to the sustainability of desert oases. It is also suggested that geoheritage studies in the oases of the Western Desert of Egypt can serve as a model for similar research in other desert domains of the world.

KEYWORDS: arid environments, geosites, North Africa, research geography, sustainable development

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INTRODUCTION

Oases play a vital role in arid and hyper-arid areas of the world. They diversify desert environments and make them habitable. It would be difficult to imagine agriculture, long-distance transportation, and tourism in deserts without oases. Their historical role was outstanding (Moore et al. 1994; Mattingly et al. 2015; Guagnin et al. 2017; Rowlands et al. 2020; Manapova 2021; Fenwick et al. 2021; Kaczmarek et al. 2024). Scientists pay a much greater attention to contemporary development, planning, and sustainability of oases (Xiao-feng and Zhe 2001; Bouaziz et al. 2018; Xue et al. 2022; Chen et al. 2023; Dhawi and Aleidan 2024) in such different regions as North Africa (Amichi et al. 2020; El-Hassanin et al. 2020), Central Asia (Bie and Xie 2020; Zhang et al. 2023), and western South America (Calderón-Seguel et al., 2021). However, the full potential of sustainable development in oases with novel types of natural resources is yet to be fully understood.

In the early 21st century, researchers recognized that geological heritage (geoheritage), which refers to peculiar geological and geomorphological features of a given territory, can be treated as an important natural (geological) resource (Bétard et al. 2017; Singtuen et al.

2019; Custódio et al. 2024; Mousa et al. 2024; Sen et al. 2024). Its conservation (geoconservation) and utilization (first of all, geotourism) contribute to sustainable development and bring socio-economic benefits (Prosser et al. 2013; Dowling and Newsome 2018; Reynard and Brilha 2018; Kubalíková et al. 2021; Xu and Wu 2022; Bressan and Lopes 2023; Soldati 2023). Beyond nature protection, enhanced education, and tourism initiatives, which are often discussed in the literature (Gupta et al. 2024; Zafeiropoulos et al. 2025), effective geoheritage management has some other important implications for sustainability. They include (but are not limited to) better awareness of traditional and renewable natural resources as an outcome of geoheritage inventories, development of transport infrastructure related to initiatives of accessibility improvement, and deeper understanding of identities of local communities rooted in heritage and symbolic meaning of geological/geomorphological objects. Importantly, many geoheritage-rich areas host sources of freshwater or serve as habitats for unique plants and animals.

Geoheritage features are rather abundant in desert domains due to better exposure and visibility of geological and geomorphological features where vegetation is

scarce or absent. Although sand and coarse debris can mask these features, the former themselves are geological phenomena and even elements of geoheritage. Inventories of geoheritage in different deserts of the world constitute an urgent task (cf. Sayama 2024).

Five reasons why oases can become targets for geoheritage studies can be outlined. First, oases are often rich in peculiar geological and geomorphological features because their existence is determined by specific geological and geomorphological settings. Second, oases retain connections with populated areas beyond deserts, and thus, they have better accessibility than other desert areas. Third, the presence of settlements in many oases makes accommodation of geoheritage researchers comfortable possible and facilitates their work by the availability of earlier accumulated geological knowledge and education centers (even universities). Fourth, many oases are distinguished by outstanding scenery, which strengthens aesthetic properties of geoheritage features and attracts visitors. Fifth, many oases have been populated for centuries, and, thus, they possess rich cultural and historical heritage that requires conservation efforts and sustainable tourist flows, which facilitate the initiation of geoconservation and geotouristic initiatives. Overall, oases can be considered geoheritage-rich areas (GRAs). Naturally, oasis-centered GRAs are not only valuable but also fragile due to desert dynamics (e.g., dune migration) and intense anthropogenic intervention (e.g., agricultural activities or abundant construction).

Countries of North Africa, including Egypt, have demonstrated significant acceleration in geoheritage studies from the mid-2000s, when the related knowledge was very limited and chiefly preliminary and qualitative (Schlüter 2006), to the beginning of the 2020s, when this knowledge had become rather extensive, detailed, and based on both qualitative and quantitative studies (Neto and Henriques 2022; El hamidy et al. 2024; Errami et al. 2024). Notably, the first works on Egyptian geoheritage appeared before a research “boom” of the past decade (Shata 1988; Coli et al. 2011; El-Asmar et al. 2012; Salama et al. 2013). The development of advanced geotourism in Egypt is a current priority (Soliman and Abou-Shouk 2017). A vast area between the Mediterranean coast in the north, the western and southern boundaries of the country, and the Nile valley in the east is covered by the Western Desert of Egypt. Many oases in this region are large in size, and they have become

targets of intense geoheritage studies (e.g., Plyusnina et al. 2016; Salama et al. 2020; Khalaf 2022).

The present paper aims to provide summarized knowledge about the oases-centered GRAs of the Western Desert of Egypt. This study employs published information and the authors' research experience. Oasis-centered GRAs beyond Egypt are also addressed in this study. This study evaluates the potential contribution of geoheritage to oasis sustainability.

STUDY AREA

The Western Desert of Egypt is a northeastern segment of the Sahara with hyper-arid environments. Groundwater discharge via springs in topographic depressions supports the existence of lakes, streams, and even waterfalls. The availability of water makes agriculture possible in these depressions, which are oases. Several relatively large oases are located in the Western Desert of Egypt (Fig. 1). Many of them are populated and possess settlements of varying size. El-Kharga City is an example of an important and growing administrative and educational center in the middle of the desert. Some oases, such as Siwa Oasis, attract numerous tourists. The oases are connected to the Nile Valley and the Mediterranean coast by roads, including paved roads of high quality with regular public transportation.

The geological setting of the Western Desert of Egypt and its oases is diverse (Crombie et al. 1997; Brook et al. 2003; Guiraud et al. 2005; Issawi et al. 2009; Tawadros 2011; Aly 2015; Said 2017; Hamimi et al. 2020, 2023; Peroschi and Cambieri 2023; Mansour et al. 2024). This territory is the northeastern edge of the African lithospheric plate, and it has been relatively stable during the entire Phanerozoic despite certain deformations and faulting. The sedimentary succession of the Western Desert is dominated by Cretaceous–Paleogene siliciclastics and carbonates that accumulated during marine incursions from the north. Continental (including alluvial) facies are also present. Precambrian crystalline and Paleozoic sedimentary rocks, as well as igneous bodies, crop out locally. Quaternary deposits are represented particularly by sand dunes, although carbonates that formed during wetter climate phases are also present. Paleontological remains are abundant in some sedimentary packages. Mineral deposits and groundwater are important geological resources, which have been exploited for local and national needs.

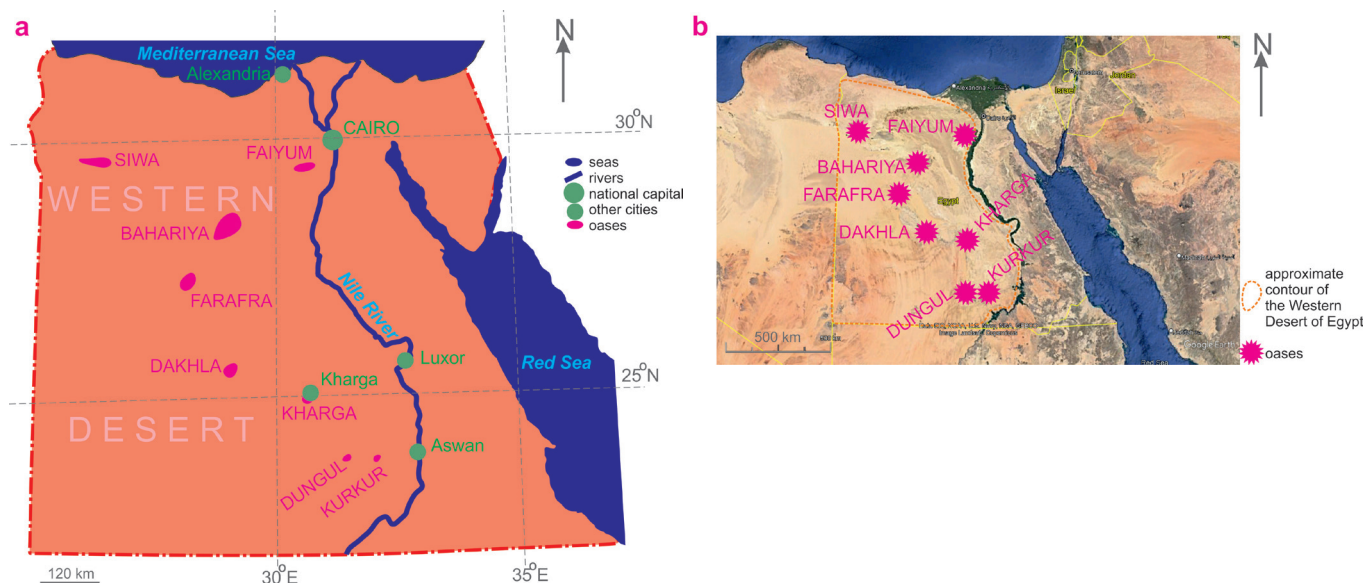


Fig. 1. Geographical location of the considered oases of the Western Desert of Egypt:
a – general location map, b – satellite image¹

¹ Source: Google Earth Pro.

MATERIALS AND METHODS

Data collection

Field investigations in the majority of the oases of the Western Desert of Egypt, including assessments of geoheritage resources and inventories of geoheritage sites (geosites) were carried out over approximately a decade. The related observations and interpretations validate published knowledge of oasis geoheritage. This field-based information is essential to establish common geoheritage types and assess the completeness of the knowledge of geoheritage of each oasis.

The information about oases-centered GRAs beyond Egypt is scattered in the literature, and, thus, a selection of the relevant sources is an urgent task. The bibliographical database "Scopus", which covers scientific journals regularly publishing outcomes of geoheritage studies, was used for this purpose. A carefully constructed search formula allowed identification of the principal sources, from which irrelevant ones were then deleted (Fig. 2). Indeed, the obtained set of works cannot be exhaustive (this is typical of all bibliographical surveys), but the sample is sufficient for the present analysis. The full text of each relevant source was checked to systematize the knowledge of oases-centered GRAs.

Basic procedures

Descriptions of geoheritage of the considered oases of the Western Desert of Egypt and beyond can be found in the literature (summarized below). They are not repeated in the present work, although some distinctive features and the compiled lists of sources are provided. Attention is paid to two general characteristics of GRAs, namely geoheritage exploration and main geoheritage types. These characteristics reflect "maturity" and content of the considered GRAs.

Although the basic principles of a territorial geoheritage assessment and inventory are well-developed (Prosser et al. 2006; Reynard and Brilha 2018; Song et al. 2023; Štrba et al. 2023; Zorlu et al. 2023; Ferrer et al. 2024; Kubalíková 2024), the really used approaches may differ significantly depending on research tasks, accessibility, and natural contexts. The published studies dealt with:

- 1) A single geosite of a given area;
- 2) A few geosites (randomly selected or sharing common attributes) of a given area;
- 3) As many geosites of a given area as possible;
- 4) Potential existence of geosites;
- 5) Diversity of local geological and/or geomorphological phenomena and possible geoparks.

The knowledge of each given GRA develops individually, and it is characterized by distinct certainty and completeness. For the purposes of the present analysis, the options used in the previous geoheritage studies were detected.

The content of GRAs is reflected by an attribution of peculiar geological and geomorphological features available there to standardized geoheritage types. The employed nomenclature of the latter follows Ruban (2020) and includes geomorphological (landforms), tectonic (structures), stratigraphical (stratotype sections, unconformities), paleontological (fossils), sedimentary (sedimentary phenomena), paleogeographical (facies, paleoecosystems), igneous (magmatic phenomena), metamorphic (metamorphic phenomena), geochemical (geochemical anomalies), mineralogical (mineral localities), hydro(geo)logical (surface water, springs, groundwater), geothermal (hot springs, geysers), engineering (active slopes), pedological (soils), economical (mineral and energy deposits), geohistorical (history of geological exploration), geocryological (permafrost), cosmogenic (impact structures), and complex (co-existence of two and more types) types. Many types co-exist in GRAs, but the information on their number depends on the previous research (for instance, some specialists focused only on particular features and ignored the others). Moreover, the value of features belonging to different types can vary. To make the knowledge of the content of the considered GRAs consistent, three main (most valuable and characteristic) types were outlined for each oasis. Selection of these types required a careful analysis of the published information.

RESULTS

Western Desert of Egypt

A total of eight oasis-centered GRAs can be identified in the Western Desert of Egypt (see Fig. 1). In two cases, the oases are paired, and the related GRAs are close to one another. The large Bahariya and Farafra oases are located in the northern half of the desert. They possess diverse geological features, the most interesting of which include late Mesozoic–Cenozoic sedimentary rocks and the related facies, as well as karst features. The Dakhla Oasis is situated in the central part of the desert, and it is known for peculiar landforms (natural "sculptures") and specific sedimentary rocks and facies such as Late Cretaceous variegated shales (Fig. 3a). The Dungul and Kurkur oases are small, and they are found on the southeastern edge of the desert. They are famous for spectacular paleospring



Fig. 2. Procedures of literature selection for the purposes of the present study

tufa deposits of Quaternary age overlying older deposits (Fig. 3b). The Faiyum Oasis on the northeastern edge of the desert is not only large and well-populated but also the most proximal to the Nile Valley, with which it has been strongly connected since ancient times. It is well-known to paleontologists due to impressive and well-preserved skeletons of Paleogene marine vertebrates (whales) (Fig. 3c), findings of which have made this locality emblematic of the entire Egyptian geoheritage. The Kharga Oasis is large and elongated, and it is situated in the eastern part of the desert. Characteristic features include tufa deposits of ancient springs indicating much wetter conditions in the Quaternary (Fig. 3d). Finally, the Siwa Oasis lies in a deep depression (below sea level) in the northwestern part of the desert, and it is famous for its rich cultural history going back to the pharaonic kingdoms and Alexander the Great. Geologically, it is known, primarily, for outcrops of Miocene

carbonate rocks (Fig. 3e) and active evaporite deposition in several lakes (Fig. 3f).

The analysis of the published studies shows that the considered oases of the Western Desert of Egypt differ in geoheritage exploration (Table 1). The information on the GRAs corresponding to the Bahariya, Farafra, Faiyum, and Siwa oases appears most certain and complete. On the one hand, their geoheritage potential was studied comprehensively. On the other hand, many geosites were already proposed. In the cases of the Dungul and Kurkur oases, the situation is different. There, the geoheritage potential was examined with similar attention, but only selected geosites were proposed, and they were neither described formally nor assessed. Therefore, additional investigations are necessary to expand the information in these GRAs. The quality of information on Kharga and especially Dakhla oases is poorer. In the former, almost



Fig. 3. Examples of geoheritage from the different oases of the Western Desert of Egypt:
a – a small isolated landform exhibiting Campanian (Cretaceous) variegated shales (Dakhla Oasis),
b – Quaternary tufa deposits overlying unconformably Maastrichtian (Cretaceous) shales (Dakhla Formation),
c – a skeleton of an Eocene (Paleogene) cetacean (Faiyum Oasis), d – exposures of Quaternary tufa deposits indicating a wetter local paleoclimate (Kharga Oasis), e – Miocene (Neogene) carbonates exposed on slopes of a large residual hill (Siwa Oasis), f – coast of the Siwa lake (Siwa Oasis). All photographs were made by E.S. Sallam

randomly established geosites were proposed, and a single geosite was proposed in the latter. Thus, these GRAs need analyses of their geoheritage potential, and more geosites can be found there. Full-scale, field-based investigations are necessary to fill these gaps. The summarized evidence suggests that simultaneous or successive geoheritage studies by two or more research teams in the same oasis-centered GRAs and applications of different approaches have led to more robust and comprehensive knowledge.

The content of the GRAs in the Western Desert of Egypt differs. Sedimentary, paleogeographical, and geomorphological types are the most common geoheritage types. However, the Bahariya, Faiyum, and Siwa oases possess some other types (igneous, paleontological, and hydro(geo)logical types, respectively), which are important only in them. The detailed analysis of the works dealing with the considered GRAs (see sources in Table 1) implies that almost all geoheritage types exist in the Western Desert of Egypt, except for the geocryological type (indeed, permafrost is improbable in hyper-arid environments) and the cosmogenic type (more research is necessary to realize a presence/absence of impact structures in this desert). The quantity of information from the Dakhla and Kharga oases does not permit documentation of the range of geoheritage types.

Beyond Egypt: Africa and the rest of the world

Several oases-centered GRAs exist beyond Egypt (Table 2). Half of them are situated in North Africa (Morocco and Tunisia), 40% are located in the Middle East, and a single GRA is known from western South America (Chile). Indeed, many oases exist in the deserts of Australia, Central Asia (especially western China), western North America, and South Africa; Antarctica

is also a desert with oases, although of a different type. This suggests that either the corresponding geoheritage has yet to be explored or its relevance to oasis environments was not stressed in the publications. Nonetheless, a quasi-global occurrence of oasis-centered GRAs is evident despite the noted knowledge gaps.

The considered oasis-centered GRAs established beyond Egypt differ in geoheritage exploration (Table 2). The only Hingol area of Pakistan boasts really comprehensive information about its geoheritage resources. In many cases, attention was paid to either particular geosites or particular geoheritage types (e.g., geomorphological). From two GRAs, only single geosites (although large and complex) were reported. Generally, the quality of the information is moderate, with uncertainties (when only potential was considered) or incompleteness (when only a few geosites were proposed). The sources indicated in Table 2 show significant differences in the approaches and researchers' goals. Notably, a few works discuss either established or proposed geoparks.

The content of the considered GRAs differs. The geomorphological and sedimentary types are the most common geoheritage types, and the paleogeographical and hydro(geo)logical types are also rather frequent. One should note that more than a half of the considered GRAs represent the types other than those above-mentioned.

DISCUSSION

Sustainability perspectives: a conceptual ground

Various aspects of sustainability linked to various Sustainable Development Goals specified by the United Nations (Wackernagel et al. 2017; Leal Filho et al. 2019; Bandari et al. 2022; Jarrah et al. 2024; Raman et al. 2024),

Table 1. Geoheritage in the oases of the Western Desert of Egypt. The knowledge is valid for mid-2024. See the location of the oases in Fig. 1

Oasis (area, km ² ; main settlement)	Geoheritage exploration*	Three main geoheritage types	Remoteness from the Nile valley	Source(s)**
Bahariya (~2000, El Bawiti)	Assessed resources	Sedimentary, paleogeographical, igneous	Significant	Salama et al. (2013), Plyusnina et al. (2016), Khalaf et al. (2019), Mousa et al. (2023)
Dakhla (~2000; Mut)	Single geosite proposal	Geomorphological, paleogeographical, sedimentary	Significant	AbdelMaksoud et al. (2020)
Dungul (~22; uninhabited)	Several geosite proposals; potential revealed	Sedimentary, paleogeographical, geomorphological	Significant	Sallam et al. (2018b)
Faiyum (~1700; Faiyum city)	Assessed resources	Paleontological, paleogeographical, geomorphological	Moderate	Sallam et al. (2018a); Khalaf and El-Kheir (2022)
Farafra (~1000; Farafra city)	Assessed resources	Sedimentary, paleogeographical, geomorphological	Very significant	Plyusnina et al. (2016), Salama et al. (2020), Khalaf (2022), Mousa et al. (2023)
Kharga (>5000; El Kharga city)	Several geosite proposals	Sedimentary, paleogeographical, geomorphological	Significant	Mousa et al. (2024)
Kurkur (>30; uninhabited)	Several geosite proposals; potential revealed	Sedimentary, paleogeographical, geomorphological	Significant	Sallam et al. (2018b)
Siwa (~200; Siwa city)	Assessed resources	Hydro(geo)logical, sedimentary, paleogeographical	Very significant	Sallam et al. (2018a), Ahmed (2023)

Notes:

*See text for more explanations.

**Due to the engagement of the authors in geoheritage studies in all mentioned oases, they cite a minimal number of their own works.

Table 2. Geoheritage in the desert oases beyond Egypt. The knowledge is valid for mid-2024

Oasis or oasis-related area (country; abbreviation)	State of geoheritage exploration*	Three main geoheritage types*	Geopark options*	Source
Al-Ahsa (Saudi Arabia)	Single geosite proposal	Geomorphological, engineering, sedimentary	No	Sen et al. (2023)
Azraq (Jordan)	Briefly characterized potential	Hydro(geo)logical, igneous, sedimentary	Proposed	Mohammad et al. (2023)
Errachidia (Morocco)	Several geosite proposals	Tectonic, paleogeographical, geomorphological	No	Si Mhamdi et al. (2023)
Hingol (Pakistan)	Assessed resources	Sedimentary, geomorphological, stratigraphical	Proposed	Yaseen et al. (2021)
Jebel Hafit (UAE)	Single geosite proposal	Geomorphological, tectonic, paleogeographical	No	Giusti et al. (2023)
Nefzaoua (Tunisia)	Partly assessed resources	Hydro(geo)logical, geomorphological, economic	No	Raddadi and Podwojewski (2022)
Oued Noun (Morocco)	Several geosite proposals	Sedimentary, hydro(geo)logical, igneous	No	Mirari and Benmlih (2021)
Pica (Chile)	Partly assessed resources	Hydro(geo)logical, sedimentary, geomorphological	No	Lictevout et al. (2020)
Tata (Morocco)	Briefly characterized potential	Paleogeographical, geomorphological, sedimentary	Established	Berred and Berred (2021)
Tozeur (Tunisia)	Several geosite proposals	Geomorphological, paleogeographical, economic	No	De Waele et al. (2005)

Note:

*These characteristics follow the only indicated sources.

were reported from the majority of the considered oases of the Western Desert of Egypt. Their diversity is impressive, and the majority of these aspects are linked to sustainable agriculture, water, and energy (Table 3). Similarly, some aspects of sustainability were addressed in oasis-centered GRAs beyond Egypt (e.g., Mohammad et al., 2023). Sustainable development in oases requires the use of all relevant resources available locally. The previous research in Egypt (e.g., Sallam et al. 2018a; Khalaf et al. 2019) and beyond (De Waele et al. 2005; Si Mhamdi et al. 2023) has stressed that geoheritage is among such resources.

The idea of GRAs indicates that oases do not possess but concentrate geoheritage resources and make their effective exploitation possible. There are many directions and opportunities to use these resources, and this exploitation can contribute to sustainable development more rapidly (Fig. 4). For instance, many oases need improvements in agricultural practices (regarding land degradation) and groundwater management (Table 2). If rich geoheritage resources are available, their use will almost automatically require better local planning, which requires improvements in overall environmental management. Experts with advanced knowledge and skills will be engaged in such planning. Moreover, financial benefits from geoheritage-triggered tourism (not only geotourism) will extend locally available funds for innovative environmental management. In such a situation, the potential for positive changes in agriculture and groundwater use increases.

The presence of geoheritage resources in the Western Desert of Egypt and many other arid/hyper-arid areas was recognized relatively recently, and, thus, the use of these resources for sustainable development can only be proposed. It would be difficult to register actual cases. Nonetheless, two conceptual examples can be provided. First, the use of geothermal resources for energy generation and sustainable transition has remained on the agenda

in the Western Desert of Egypt (Abdel Zaher et al. 2018; Elmasry et al. 2022) and its oases (Mohamed and Zaher 2020; Arafa-Hamed et al. 2023; Ghoneim et al. 2023). The related developments depend on the understanding of the local geological settings. The latter can be determined much more precisely in the course of geoheritage investigations requiring accurate documentation and inventory of small-scale features. Second, Soliman and Abou-Shouk (2017) noted government interest in the development of non-traditional tourism, to which geotourism also belongs, and the attraction of international visitors. Indeed, the related activities require a full-scale exploration of geoheritage resources, as well as their active promotion. Considering behavioral attributes of foreign tourists (Soliman and Abou-Shouk 2017) will contribute to geotourism growth.

Two examples demonstrating the already started contribution of oases-centered GRAs to sustainable development can also be proposed. First, several GRAs, such as the Bahariya and Faiyum oases, have already been used for enhancing education. Particularly, field educational campaigns were organized for university students, and geosites representing “ideally” some geological phenomena and concepts served ideally in the explanations of these phenomena and concepts. This not only strengthened knowledge and skills and contributed to more professional and, thus, sustainable exploitation of the geological environment but also cultivated better awareness of Egyptian geoheritage, which is related to national pride. Second, the UNESCO World Heritage Site Wadi El Hitan in the Faiyum Oasis has fostered international collaboration of scientists and, thus, strengthened the inflow of intellectual capital to the country. It should be noted that accumulation of such capital correlates with environmental sustainability (Delgado-Verde et al. 2025; Gidage and Bhide 2025). As stated by Gingerich (2024), this geosite has outstanding importance to science

Table 3. Examples of the sustainability aspects in the oases of the Western Desert of Egypt

Oasis*	Sustainability aspect	Theme	Related UN SDG**,***	Source(s)
Bahariya	Geothermal potential	Sustainable energy	SDG7: Affordable and clean energy	Mohamed and Zaher (2020)
	Groundwater quality and vulnerability	Sustainable water	SDG6: Clean water and sanitation	Masoud and El Osta (2016), Sharaky and Abdoun (2020)
Dakhla	Soil erosion	Sustainable agriculture	SDG2: Zero hunger	Selmy et al. (2021)
	Possible groundwater depletion			Kimura et al. (2020)
Faiyum	Cultivated land degradation / land use changes	Sustainable agriculture	SDG2: Zero hunger	Ali et al. (2013), Atef et al. (2024)
	Quality of life concerns	Sustainable people's life	SDG3: Good health and well-being	El Sary and El-Sherbiny (2024)
	Lake productivity	Sustainable fishery	SDG14: Life below water	Napiórkowska-Krzebietke et al. (2016), Mohamed et al. (2022)
	Tourism sustainability potential	Sustainable tourism	SDG12: Responsible consumption and production	Ramzy (2013)
Farafra	Geothermal potential	Sustainable energy	SDG7: Affordable and clean energy	Arafa-Hamed et al. (2023)
	Urban sustainability solutions			Abouelfadl et al. (2014)
	Desertification / land degradation	Sustainable agriculture	SDG2: Zero hunger	Abuzaid et al. (2021), Fadl et al. (2022)
	Groundwater management	Sustainable water	SDG6: Clean water and sanitation	Moharram et al. (2012)
Kharga	Agricultural water use	Sustainable agriculture	SDG2: Zero hunger	El-Shirbeny et al. (2021)
	Renewable sources of electricity production (wind power)	Sustainable energy	SDG7: Affordable and clean energy	Ahmed (2019)
Siwa	Geothermal potential	Sustainable energy	SDG7: Affordable and clean energy	Ghoneim et al. (2023)
	Tourism, local communities, environment	Sustainable tourism	SDG12: Responsible consumption and production	Ayad and Ye (2012), Tawfik (2016), Elgammal (2022)
	Lake bioinvasion	Sustainable fishery	SDG14: Life below water	Saber et al. (2022)
	Groundwater use	Sustainable agriculture	SDG2: Zero hunger	Moghazy and Kaluarachchi (2021)
	Maximizing crop production			Moghazy and Kaluarachchi (2020)

Notes:

*The information was found for only some oases of the Western Desert.

**UN SDG is a United Nations Sustainable Development Goals².

***The possible relations of the registered sustainability aspects and themes to the UN SDG are interpreted for the purposes of this study.

²Source: <https://sdgs.un.org/goals>.



Fig. 4. Conceptual representation of the importance of GRAs for sustainable development of oases. The ideas are based on the authors' own and previous interpretations (see sources summarized in Tables 1 and 2)

and public education due to excellent representation of Eocene tropical ecosystems. Indeed, learning about them contributes to the understanding of environmental sustainability and, particularly, the ideas of global climate changes and their wide environmental effects.

Indeed, the possible utility of oasis-centered GRAs to sustainable development is a conceptual idea (see Fig. 4). Two practical questions are who can launch the supposed initiatives and how. First, geoheritage resources of oases should be explored much better, which requires a regular activity of several research groups. If so, state, regional, and municipal governments and other official authorities interested in sustainable development should create opportunities (official research initiatives and grants, logistic support) for geoheritage studies in oases. Second, the ideas of geoheritage need better circulation among the national scientific community and tourism professionals in Egypt. Geologists should be ready to use the information generated by geoheritage experts, and tourist firms should be ready to launch geotourism programs. Third, the relevance of geoheritage resources to the sustainable development of oases needs comprehensive investigations, and the outcomes of this research have to be communicated to national and local policymakers. Indeed, only large, multidisciplinary, and government-supported project(s) can enable the achievement of these tasks. Research and educational institutions already existing in the oases of the Western Desert of Egypt can play a leading role. Mousa et al. (2024) already stressed the importance of New Valley University in the Kharga Oasis.

Geoheritage studies in the Western Desert of Egypt as a model

A comparison of the knowledge of the oasis-centered GRAs of the Western Desert of Egypt (Table 1) and the rest of the world (Table 2) implies that the former performs well in terms of the number of such GRAs and the quality of information about them. Indeed, geoheritage studies in Egypt have already developed a systematic vision of the national geoheritage. Different approaches have been

permitted to address multiple aspects of geoheritage resources. These are premises to propose the Western Desert as a model for geoheritage studies in oases.

Three basic features of the above-mentioned model are as follows. First, an oasis is understood as a concentrator of geoheritage features in a desert environment, and it is studied entirely, as well as its vicinities. Second, more general and more specific geoheritage-related projects are realized simultaneously or successively. Third, geoheritage studies do not miss other kinds of natural and cultural heritage of oases (it is a norm when geological and cultural heritage coincides (e.g., Sallam et al. 2018a, b)) and pay attention to sustainability aspects (see Table 3). More generally, a comprehensive exploration of the geoheritage of deserts is reasonable to start from oases, expanding investigations to spaces around and between them.

Achievements in the understanding of the oasis-centered GRAs in the Western Desert of Egypt (see Table 1) deserve comparisons to the experience in some other countries (see Table 2). This task can be achieved via special workshops or international collaborative projects.

CONCLUSIONS

The present summary of the knowledge of geoheritage from several oases of the Western Desert of Egypt and some other regions of the world permits three general conclusions:

- 1) oases concentrate diverse geoheritage features;
- 2) a total of eight GRAs known from the Western Desert of Egypt differ in geoheritage exploration and content, and the same is true for GRAs in the other regions of the world;
- 3) GRAs of the Western Desert of Egypt can be related to sustainable development of oases.

The perspectives for future investigations are linked, particularly, to studying geoheritage distribution in oases, relations between geoheritage and sustainability, and opinions of stakeholders in the fields of geoheritage management and sustainable development. Understanding the suitability of oases for the creation of geoparks is also an important research task. ■

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DECLINE IN TRADITIONAL FODDER AVAILABILITY AND SHIFT TO ALTERNATIVE FODDER SUPPLEMENTS FOR LIVESTOCK IN CHAMOLI DISTRICT, UTTARAKHAND, INDIA

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ABSTRACT. The Himalayan region's traditional fodder systems are under increasing strain from socioeconomic shifts and environmental change. This study examines the changing dynamics of fodder availability and livestock management in Chamoli district, Uttarakhand (India). The study was conducted in five blocks of the district (Joshimath, Pokhari, Karnaprayag, Tharali, and Dewal). These covered different elevation zones: lower (800–1,500 m), middle (1,500–2,500 m), and higher (>2,500 m). The research employed household surveys (n=150) to examine trends in traditional fodder resources, adaptation strategies, and associated challenges. Findings reveal a 37% decline in overall fodder availability since 1990, with the highest reduction (45%) in higher regions due to climate change and decreasing snowfall. Mid-altitude areas experienced a 38% decline, largely due to restricted forest access and invasive species. The lower zones reported a 29% decrease, which was driven by agricultural expansion and deforestation. The study highlights a 105% increase in fodder collection (from 2.1 to 4.3 hours daily) as well as a doubling of collection distances (from 1.8 to 3.6 km) over three decades. Periods of acute shortage extended from 2.3 to 4.7 months annually. This increase disproportionately impacts women's workloads. Households have responded by adopting alternative strategies, including commercial feed (63% adoption), increased reliance on crop residues (88%), and herd reduction (97%). Household income, market access, and education significantly influence adaptation capacity. These findings underscore the urgent need for targeted interventions, such as improved fodder cultivation, integrated fodder development programs, enhanced forest management policies, and economic support for dependent populations. This research contributes to understanding social-ecological transitions in mountain systems.

KEYWORDS: fodder, Himalayas, livestock, high altitude, agriculture

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INTRODUCTION

Livestock rearing forms an integral component of rural livelihoods in the Himalayan region of Uttarakhand. The traditional agro-pastoral systems have sustained Himalayan communities for generations (Singh et al. 2015). Despite the significance of livestock rearing in the region, forage cultivation has received minimal attention. Instead, grazing in forest areas, subalpine pastures, and alpine pastures remains the primary source of fodder for animals (Aryal et al. 2014). Historically, forests and natural grasslands have provided the bulk of fodder for livestock,

with well-established seasonal variations in fodder collection strategies (Wrobel et al. 2025). In addition to natural grazing, fodder trees and shrubs play a crucial role in meeting livestock dietary needs, particularly during periods of scarcity. These traditional fodder sources have long supported rural livelihoods and livestock productivity. However, their availability is increasingly challenged by environmental and socioeconomic changes (Saeed et al. 2022). In recent, significant transformations have occurred in fodder availability patterns, forcing farmers to adapt their livestock management practices. The Central Himalayan landscape of the Chamoli district presents diverse

geographical features ranging from valleys to high-altitude meadows, supporting an economy that is predominantly agrarian, with animal husbandry contributing significantly to household income and food security (Kumar et al. 2025a).

Traditional fodder resources in this region include forest leaf litter, tree fodder, grasses from community lands, and crop residues from agricultural fields (Katoch 2022; Khan et al. 2025). These resources have not only supported livestock but have also played important roles in enhancing human health and nutrition through the livestock products they enable. Several studies, such as Katoch et al. 2022, Ahmad et al. 2018, Kumar et al. 2025b, and Kumar et al. 2026 have documented how changing environmental and socioeconomic conditions are affecting fodder availability in the Himalayan regions. The decline in traditional fodder availability has become a serious issue in many livestock-dependent regions. This has prompted a shift toward alternative fodder supplements for livestock. Climate change, environmental degradation, land-use changes, and policy restrictions have contributed to the depletion of natural fodder sources (Pandey et al. 2014). The variability in precipitation patterns, reduced snowfall, and shifting vegetation zones have affected the natural regeneration and productivity of fodder species. Studies on fodder plants in the Joshimath area of Chamoli district have reported significant declines in several important species. These have raised concerns about their availability and ecological implications (Tiwari & Rawat 2017). Similar trends have been observed in neighboring regions, where studies have reported a rapid decline in forest-based fodder availability. These studies attribute the decline to climate change, forest degradation, and policy restrictions (Negi et al. 2019). The socioeconomic dimensions of these changes are equally significant. The adaptation strategies to resource scarcity are strongly influenced by socioeconomic status, landholding size, and market accessibility (Mohamed et al. 2020). Research indicates a reduction in traditional fodder resources in the Garhwal region of Uttarakhand, highlighting a broader trend across the Central Himalayas. This decline has been further intensified by outmigration, shifting livelihood patterns, and reduced labor availability for fodder collection (Sharma et al. 2023; Islam et al. 2023). In response to these challenges, farmers have increasingly turned to cultivated fodder crops, commercial feed, and agro-industrial by-products to sustain livestock. While these alternatives offer short-term relief, concerns remain about their long-term sustainability, particularly for small-scale farmers with limited financial resources (Kumar et al. 2025b). Households with improved cattle breeds are more likely to purchase commercial feed, while those with traditional livestock varieties attempt to maximize the use of available natural resources. This suggests a relationship between livestock breed selection and fodder management strategies that merits further investigation in the Chamoli context.

Critical perspectives on these transitions emphasize concerns about the sustainability of current adaptation trends, particularly regarding increasing economic vulnerability among resource-poor households and the potential long-term ecological impacts of intensive fodder cultivation systems. These concerns are especially significant in the context of social-ecological resilience and sustainability. Despite these advances in understanding, significant knowledge gaps remain regarding the complex interactions between climate change, forest management policies, socioeconomic transformations, and fodder availability (Katoch 2022). Most existing studies have

either focused on broader regional patterns or on specific aspects of the fodder system. There is a lack of information on how much traditional fodder sources have actually declined in Chamoli and how people are adjusting to feed their livestock. The mitigation strategies and challenges adopted by poorer households and wealthier households may also differ. This study fills these gaps in several ways. It documents changes in traditional fodder availability and identifies which alternative feeding practices households have started using. It examines how households have adopted each approach from buying commercial feed to growing their own fodder. Since not all households have the same resources, the study compares how deprived and well-off households differ in strategies. In addition to wealth, the study examines additional variables that may facilitate or impede adaptation, such as the number of livestock kept by a family, their educational attainment, the distance from markets, etc. Together, these provide a more comprehensive understanding of the problem and the many approaches being used by households. Understanding these patterns can help design inclusive programs that work for mountain communities.

STUDY AREA

The study was conducted in Chamoli district, Uttarakhand, which covers an area of approximately 8,030 km² in the Central Himalayan region. The district has elevations ranging from 800 to 7,817 meters above sea level. The research encompassed five distinct blocks within the district (Joshimath, Pokhari, Karnaprayag, Tharali, and Dewal), each representing different ecological characteristics and farming systems. The Joshimath block is situated in the higher elevational zone. It is characterized by alpine meadows, influencing seasonal livestock migration patterns. The Pokhari block is located in the middle elevational zone and features mixed oak and rhododendron forests that serve as important fodder sources for local communities. The Karnaprayag block represents transitional ecology between lower and middle zones, with terrace farming being predominant. The Tharali block in the middle zone is known for its extensive community-managed forest areas that play a crucial role in regulated fodder collection. The Dewal block has subtropical vegetation and more intensive agricultural practices with crop residues forming a significant portion of livestock feed. These blocks were strategically selected to represent the full spectrum of fodder management systems practiced across different ecological niches in the Himalayan region.

METHODOLOGY

Sampling Design and Data Collection

The study covered five different blocks in the district (Joshimath, Pokhari, Karnaprayag, Tharali, and Dewal). Fifteen villages were selected across three elevational zones: lower (800-1,500 m), middle (1,500-2,500 m), and higher (above 2,500 m) to capture the diversity of fodder conditions and livestock management practices (Table 1). The study employed a multi-stage sampling approach to ensure a representative selection of participants. Specific study areas were purposively selected to capture variations across different elevational zones. Afterwards, a random selection of villages was conducted within these areas to ensure geographical diversity. Then, systematic random sampling was used to select households, ensuring that the sample accurately reflected the local community's

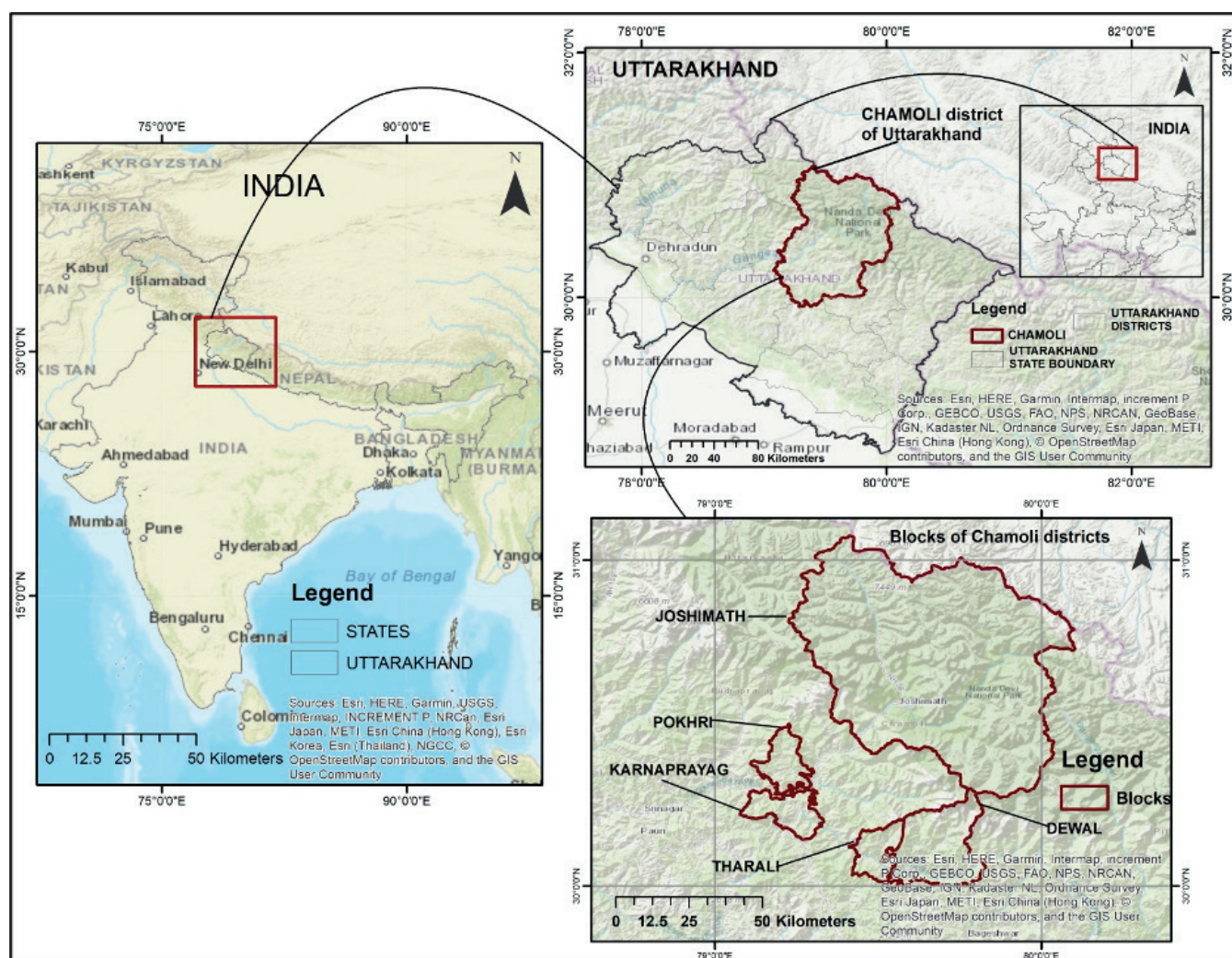


Fig. 1. Study Area

demographic and landholding patterns. Surveys were conducted with 150 households (10 households from each village and 50 households in each elevation zone). The data were collected on family demographics, livestock ownership, land use, fodder collection practices, alternative feeding methods, and the costs of maintaining livestock. For comparative analysis of adaptive strategies across socioeconomic strata, sampled households were classified into two economic categories based on total annual household income. Households were categorized as deprived if their annual household income fell below ₹60,000 (approximately ₹5,000 per month or ₹1,000 per capita per month for an average household of 5.3 members). This threshold was determined based on the rural poverty benchmarks for mountainous regions of Uttarakhand, approximating the per capita monthly consumption expenditure of ₹1,632 reported for rural areas in India (Ministry of Statistics and Programme Implementation, 2024). Households with annual income at or above ₹60,000 were classified as well-off.

Fodder use was measured using standard units, such as head loads for forest fodder and other fodder types. The amount of fodder, fuelwood, or other agricultural products balanced on the head in a single journey is referred to as the head load. This method of manual transportation is common in rural communities (Singh et al. 2021). One head load typically weighs 20–25 kg for fresh green fodder, representing the standard unit of measurement for quantifying fodder collection (Heglund & Willems 1995). This study estimates the fodder reduction using a single head load of 15 kg. Time taken by the households

to collect fodder was tracked and estimated based on observation. In addition to surveys, the research included in-depth discussions with elderly individuals and group discussions with 8–10 participants in each of the blocks with local communities. Direct observation of fodder collection practices further validated survey responses and provided a deeper understanding of the challenges faced by villagers. This mixed-method approach enabled gathering both quantitative data and detailed qualitative insights into local practices.

Data Analysis

Statistical analysis was performed using SPSS and STATA software. Descriptive statistics were calculated to characterize the sample and summarize key variables to compare current fodder availability with retrospective data from 1990 (based on respondent recall). Chi-square tests examined the association between household socioeconomic characteristics (economic status, education level, landholding size) and adoption of alternative fodder sources. Pearson correlation coefficients were calculated to determine relationships between key variables such as fodder availability, collection time, household income, and livestock numbers. Qualitative data were analyzed using thematic content analysis. Triangulation of quantitative and qualitative data strengthened the validity of findings. The integration of these analytical approaches enabled a comprehensive assessment of the decline in traditional fodder availability and the transition to alternative feeding strategies in the study area.

Table 1. Sampling Framework and Village Selection

Elevation Zone	Block	Selected Villages	Altitude (m asl)	Total per Zone
Higher (>2,500 m)	Joshimath	Mana	3,200	50
		Tapovan	2,650	
		Lata	2,550	
		Malari	3,170	
		Niti	3,200	
Middle (1,500-2,500 m)	Pokhari	Pokhari	2,200	50
		Dungar	1,950	
	Karnaprayag	Nauti	2,100	
	Tharali	Gwaldam	2,050	
		Tharali	1,900	
Lower (800-1,500 m)	Pokhari	Choundi	1,450	50
	Karnaprayag	Simli	1,350	
	Dewal	Devsari	1,250	
		Choting	1,150	
		Chaud	950	
	Total			150

Statistical Techniques Used in the Study

To assess changes in fodder availability and other indicators over time, the study used descriptive statistics to calculate mean reductions, percentages, and other descriptive measures. Fodder availability in 1990 was determined based on respondent recall (head load), while 2024 availability was measured directly during the survey period. We acknowledge that recall data may be subject to recall bias, though we attempted to minimize this by triangulating with community elders and focus group discussions. For each household in all three different elevation zones, we calculated the absolute reduction by subtracting current availability from the 1990 baseline. The mean reduction across all households was then computed by averaging these individual reductions. This means absolute reduction was converted to a percentage. For each zone, the formula was applied separately (where $n=50$ in each of three elevation zones). This decline in fodder availability across different zones was calculated using the mathematical expression as follows (Eq. 1):

$$\text{Mean Reduction} = \frac{\sum (\text{Fodder Availability in 1990} - \text{Fodder Availability in 2024})}{\text{Total Number of Observations}} \quad (1)$$

The chi-square test was used to determine whether there is a statistically significant relationship between variables, such as the relationship between household economic status and adoption of various fodder strategies. This test was applied to determine the significance of differences in the adoption rates of alternative fodder strategies between poor and well-off households. All tests had 1 degree of freedom with the significance level set at $\alpha = 0.05$ before

data analysis to maintain consistency. P-values below 0.001 are reported as such to indicate particularly strong evidence against the null hypothesis, the fundamental decision criterion remained whether $p < 0.05$ (Eq. 2) is as follows:

$$\chi^2 = \frac{\sum E(O - E)^2}{E} \quad (2)$$

where O – observed frequency in each category, E – expected frequency in each category.

To investigate the relationships between key variables (such as fodder availability, collection time, household income, education level, etc.), Pearson correlation coefficients were computed. This allowed the study to assess how strongly related different factors are to each other. This test was used to measure the strength and direction of the relationships between fodder availability, collection time, income, and other variables. Correlation strength was interpreted using standard conventions: $r < 0.3$ as weak, $0.3 \leq r < 0.7$ as moderate, and $r \geq 0.7$ as strong. The same $\alpha = 0.05$ threshold was applied, with graduated significance levels (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$) reported to indicate varying degrees of evidence against independence. Eq. (3) is as follows:

$$r = \frac{\sum (X - \bar{X}) \sum (Y - \bar{Y})}{\sqrt{\sum (X - \bar{X})^2 \sum (Y - \bar{Y})^2}} \quad (3)$$

where X and Y – variables being compared, $\bar{X}$ and $\bar{Y}$ – means of X and Y , r – Pearson correlation coefficient

RESULTS

Household and Livestock Characteristics

The demographic data reveals a traditional agricultural society in transition. The 150 sampled households exhibited diverse socioeconomic characteristics (Table 2). The average household size was 5.3 members, with 42% of households reporting at least one member who had migrated for work, likely working-age males seeking employment in urban areas. This underscores animal husbandry’s importance in the regional economy. Agriculture remained the primary occupation for 68% of households, while 22% reported livestock rearing as their main livelihood activity. The remaining 10% primarily depended on wage labor, government service, or private employment. Regarding livestock holdings, cattle (68%) and goats (61%) were the most commonly kept animals, followed by cows (42%) and sheep (18%). The average livestock holding was 4.2 livestock units per household, with significant variation based on economic status and landholding size, reflecting a balanced approach between larger, more resource-intensive animals and smaller, more resilient ones. Nearly all households (97%) reported a decline in their livestock numbers over the past decade, with a mean reduction of 36% across the sample. This represents a dramatic contraction of the livestock economy.

Traditional Fodder Resources and Availability Trends

Local communities in the Chamoli district traditionally used many different types of fodder for their livestock (forest-based fodder, agricultural by-products, cultivated fodder, etc.). They gathered leaves, branches, and plants from forests that were either protected, community-owned, or considered sacred. Oak trees, rhododendron trees, and other leafy trees were especially important sources. People also collected grasses and herbs from shared grazing areas, mountain meadows called bugyals, and unused farmland. They gathered fresh green plants during the rainy season and dried grass for winter feeding. After harvesting crops

like finger millet, barnyard millet, wheat, rice, and beans, farmers used the leftover stalks and stems as dry fodder when other food for animals was scarce. Some families also grew small amounts of fodder, mostly native grasses and useful trees along the edges of their fields. This diverse approach to fodder collection reflected the community’s deep knowledge of local ecology and seasonal changes.

Villagers developed sophisticated harvesting schedules that followed natural cycles, carefully timing when to collect from different sources to ensure sustainability. This traditional system also had social dimensions, with unwritten community rules governing access to shared resources and mutual assistance during collection. Families would often cooperate to gather and transport larger quantities of fodder from distant meadows before winter set in. The variety of fodder sources also provided nutritional balance for livestock throughout the year, with different plants offering complementary nutrients. This traditional knowledge was passed down through generations, connecting cultural practices to the practical challenges of maintaining livestock in a mountainous region with distinct seasons. The findings reveal a significant decline in traditional fodder resources across all elevation zones over the past few decades (Table 3). Due to ecological variations in vegetation density and productivity, baseline values varied by elevation zone. The results showed that the lower zones (800–1500 m) reported a mean baseline availability of 127 head loads per household per month in 1990, declining to 90 in 2024 (29% reduction). The middle zones (1500–2500 m) reported 108, which decreased to 67 (38% reduction). Whereas the higher zones (>2500 m) reported 85, which decreased to 47 (45% reduction). The analysis indicates a mean reduction of 37% in overall fodder availability since 1990, with substantial variation across ecological zones. The data demonstrates a clear pattern of fodder reduction that varies by altitude, with the higher ecological zone (>2500 m) experiencing the most severe decline (45%), primarily attributed to climate change impacts and reduced snowfall. This suggests high-altitude ecosystems may be particularly vulnerable to changing climate conditions. The middle ecological zone

Table 2. Demographic characteristics of sampled households (n=150)

Characteristics	Category	Percentage
Landholding Size	Landless (<0.1 ha)	12
	Marginal (<0.1-1 ha)	48
	Small (1-2 ha)	27
	Medium (2-4 ha)	10
	Large (>4 ha)	3
Economic Status	Deprived Households	36
	Well-off Households	64
Educational Status of Household Head	Illiterate	23
	Primary Education	31
	Secondary Education	35
	Higher Education	11

Source: Primary Survey, 2024

(1500-2500 m) shows a 38% reduction, with key factors being reduced community forest access and invasive species encroachment, indicating both anthropogenic and biological factors affecting mid-altitude regions. Lower ecological zones (800-1500 m) recorded a 29% reduction, mainly due to agricultural land conversion and forest degradation, reflecting increasing pressure on lowland ecosystems from expanding human activities. The regional variation in fodder availability appears to correlate with different driving forces: land use change dominates in lower zones, access restrictions and invasive species in middle zones, and climate-related factors in higher zones. This ecological zonation of causal factors suggests that management strategies may need to be tailored specifically to each altitude range to effectively address fodder availability challenges.

The decline in fodder availability has several important implications on local communities (Table 4). People now spend much more time gathering fodder than they did in the past. In 1990, villagers typically spent about 2.1 hours each day collecting fodder, but by 2024, this had more than doubled to 4.3 hours daily (105% increase). Villagers also have to travel much farther to find enough fodder. The average distance they walk to gather fodder has doubled from 1.8 km to 3.6 km over the study period. Additionally, the times of year when fodder is especially hard to find have become longer and more difficult. In 1990, communities faced severe fodder shortages for about 2.3 months of the year, but by 2024, these difficult periods had stretched to nearly 5 months annually. These changes show how the

decreasing availability of traditional fodder sources has created significant challenges for rural households that depend on livestock. Respondents identified multiple drivers of declining fodder availability (Fig. 2), with forest degradation (cited by 86% of households), changing rainfall patterns (78%), the reduced community access to forest resources (65%), invasive species proliferation (58%), and agricultural land abandonment (52%) being the most frequently mentioned factors. The drivers of declining fodder availability are shown in Fig. 2.

Focus group discussions and key informant interviews provided contextual insights into these changes. A 72-year-old local farmer from the Joshimath block stated:

“When I was young, we could collect a head load of oak leaves within an hour’s walk from the village. Now, the same collection takes almost the entire day, and the quality of fodder has also deteriorated. This has affected our traditional livestock-based economy.”

Adoption of Alternative Fodder Supplements

Due to the declining traditional fodder resources, households have adopted various alternative feeding strategies to meet their livestock needs. Statistical analysis using chi-square tests examined relationships between economic status and feeding strategies. Table 5 shows the adoption of alternative fodder supplements by different household categories, including effect sizes to indicate the practical significance of relationships. Commercial feed supplements show a 63% overall adoption rate, with a

Table 3. Changes in fodder availability by elevation zones, and head loads per household per month

Elevation Zone	Baseline 1990 (head loads/month)	Current 2024 (head loads/month)	Mean Reduction (%)	Primary Drivers
Lower (800-1500 m)	127	90	29%	Agricultural land conversion and forest degradation
Middle (1500-2500 m)	108	67	38%	Reduced access to community forests and invasive species
Higher (>2500 m)	85	47	45%	Climate change impacts and altered precipitation patterns
Overall	107*	68*	37%	Multiple interacting factors

*Overall values represent the mean across all 150 households.

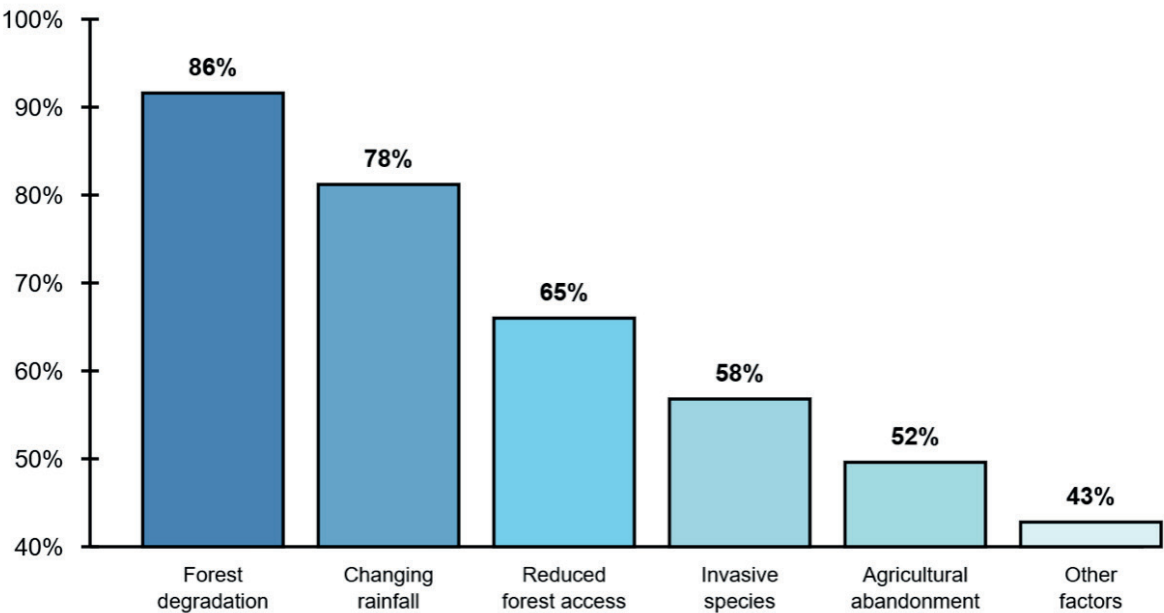


Fig. 2. Drivers of declining fodder availability (percentage of household identifying each factor)

Table 4. Fodder availability decline indicators

S. No	Indicator	1990 Value	2024 Value	Change in Percentage	Participants Perception
1	Overall Fodder Availability	106((head loads/month) loads/month)	68 (head loads/month)	-37	Severe Decline Threatening Livestock Sustainability
2	Average Fodder Collection Time	2.1 hours/day	4.3 hours/day	105	Workload Increased for Women
3	Collection Distances	1.8 km/day	3.6 km/day	100	Increased Physical Burden
4	Period of Acute Fodder Shortages	2.3 months/year	4.7 months/year	104	Extended Vulnerability for Households

Source: Computed by Author based on primary survey

Table 5. Adoption of alternative fodder supplements by different household categories

Alternative Feeding Strategy	Overall (%)	Deprived (%)	Well-off (%)	χ^2	p-value
Commercial feed supplements	63	39	77	18.7	<0.001***
Crop residues	88	94	84	3.5	0.061
Cultivated fodder	42	24	52	12.4	<0.001***
Purchased forest fodder	37	56	27	14.2	<0.001***
Reduced livestock numbers	97	100	96	2.1	0.147
Changed livestock composition	72	65	76	2.8	0.094

Note: All chi-square tests conducted with df = 1. Significance level set at $\alpha = 0.05$. *** indicates $p < 0.001$.

stark contrast between poor households (39%) and well-off households (77%). The chi-square test indicates a very strong and statistically significant relationship ($\chi^2 = 18.7$, $p < 0.001$), demonstrating that commercial feeds are substantially more accessible to wealthier households, likely due to their higher purchasing power. The medium-to-large effect size confirms this is not only statistically significant but also practically meaningful. Crop residues are the most adopted strategy overall, with an 88% adoption rate. Poor households show slightly higher adoption (94%) compared to well-off households (84%). However, this difference is not statistically significant ($\chi^2 = 3.5$, $p = 0.061$), suggesting that crop residues are universally accessible regardless of economic status, as they are the most readily available local resource for both economic groups. Cultivated fodder has a moderate adoption rate of 42%, with only 24% of poor households using it compared to 52% of wealthier ones. This highly significant difference ($\chi^2 = 12.4$, $p < 0.001$) indicates a medium effect size, suggesting that cultivating fodder requires resources such as land, agricultural inputs, and technical knowledge that are substantially less available to economically disadvantaged households. Purchased forest fodder is adopted by 37% of households overall, used much more by poor households (56%) than well-off ones (27%). This statistically significant difference ($\chi^2 = 14.2$, $p < 0.001$) shows a medium effect size and may reflect the affordability of forest fodder and local availability for poorer households who cannot afford commercial feed alternatives.

Reduced livestock numbers are nearly universal (97% overall adoption), with 100% of poor households and 96% of well-off households reporting this practice. The small difference is not statistically significant ($\chi^2 = 2.1$, $p = 0.147$), indicating that reducing herd size is a universal response

to feed scarcity across all economic groups, irrespective of household wealth. Changed livestock composition is adopted by 72% of households (65% of poor households and 76% of wealthier ones). This difference shows a trend toward higher adoption among wealthier households but is not statistically significant at the conventional 0.05 level ($\chi^2 = 2.8$, $p = 0.094$). This suggests that changing livestock type is a relatively accessible and flexible adaptation strategy for households across different economic levels. The analysis demonstrates that economic status has a pronounced influence on the adoption of resource-intensive feeding strategies like commercial feed and cultivated fodder, while poorer households show greater reliance on locally available resources like crop residues and forest fodder. Herd reduction appears to be a universal coping mechanism regardless of economic capacity. These findings emphasize the need for inclusive support mechanisms that address both financial constraints and knowledge barriers to improve fodder security for all households, particularly those with limited economic resources.

Relationships Between Key Variables

Correlation analysis provided insights into the relationships between various factors affecting fodder availability and adaptation strategies (Table 6). The analysis revealed important relationships between variables affecting fodder availability and adaptation strategies in the study area. Fodder availability showed a strong negative correlation with collection time ($r = -0.78$, $p < 0.001$), indicating that when fodder is more readily available, households spend significantly less time gathering it. This suggests that fodder scarcity creates a substantial time

burden on rural families. Household income showed a weak but significant positive correlation with fodder availability ($r = 0.21, p < 0.05$), suggesting wealthier households have slightly better access to fodder resources, possibly due to their ability to invest in various fodder acquisition methods. More notably, household income had a moderately strong negative correlation with collection time ($r = -0.34, p < 0.01$), showing that higher-income households spend considerably less time collecting fodder, likely because they can afford alternative sources or have more efficient collection methods. Livestock numbers correlated positively with fodder availability ($r = 0.43, p < 0.01$), indicating a bidirectional relationship where better fodder access enables larger herds or households with more livestock prioritize securing adequate fodder resources. Education level proved significant, showing positive correlations with both commercial fodder use ($r = 0.48, p < 0.01$) and cultivated fodder adoption ($r = 0.45, p < 0.01$), demonstrating that more educated households are more likely to purchase commercial fodder and implement fodder cultivation practices, possibly reflecting greater awareness of improved agricultural techniques. Market distance negatively correlated with commercial fodder use ($r = -0.53, p < 0.01$) but positively correlated with cultivated fodder adoption ($r = 0.37, p < 0.05$), showing that geographical isolation limits access to purchased fodder but encourages self-sufficiency through home-grown alternatives. Household income strongly correlated with commercial fodder use ($r = 0.64, p < 0.001$), cultivated fodder adoption ($r = 0.57, p < 0.001$), and livestock numbers ($r = 0.36, p < 0.05$), highlighting how economic capacity enables households to diversify their fodder management strategies and maintain larger livestock holdings. Collection time was negatively associated with commercial fodder use ($r = -0.28, p < 0.05$), cultivated fodder adoption ($r = -0.31, p < 0.01$), and livestock numbers ($r = -0.39, p < 0.01$), suggesting that high time burdens for fodder collection may restrict households' ability to invest in alternative fodder strategies or maintain optimal herd sizes. These findings illustrate how socioeconomic factors interact with fodder management approaches and could inform targeted interventions to improve fodder availability, particularly for resource-constrained households in the study region.

Economic Implications of Changing Fodder Practices

The scarcity of traditional fodder and transition to alternative fodder sources has not only reshaped livestock management practices but also had significant economic implications for households in the region. As communities

have shifted from reliance on traditional fodder sources to other commercial feed and supplements, the economic burden on households has increased substantially. The average annual expenditure on purchased fodder and feed supplements has surged from 1990 to 2024. Based on household surveys, fodder-related expenditure varied substantially across economic groups. Poor households reported spending approximately 11% of their total income on fodder and feed supplements, compared to 5% among well-off households, indicating a disproportionate economic burden on vulnerable families. This gap reflects not just different spending levels but fundamentally different coping strategies. The wealthier households could afford commercial feeds and cultivated fodder, while poorer households relied more heavily on time-intensive collection of free resources or other alternatives like crop residues. The financial strain goes beyond direct costs. Many poor households have reduced their herd sizes or shifted to less productive but less demanding livestock simply because they could not sustain the feeding expenses. Women in these households face particular challenges, spending significantly more hours each day on fodder collection as traditional sources became scarcer and more distant from villages. Traditionally responsible for fodder collection, women now report spending an average of 2.2 additional hours daily on this task compared to a decade ago. This increased time commitment has implications for women's participation in other productive activities, affecting their overall workload and potentially limiting their opportunities for income generation or personal well-being. The growing economic burden of alternative fodder sources may have broader consequences for rural livelihoods, particularly for low-income households that may struggle to afford increasingly expensive feed. This economic burden of alternative fodder sources presents a critical challenge for rural mountain communities, particularly in regions like the Chamoli district where traditional livestock management practices are rapidly transforming. As a result, there is a need for sustainable, cost-effective alternatives that not only reduce the economic strain on families but also support ecological conservation. Agroforestry practices, improved fodder management, and community-based resource management may offer solutions to mitigate these economic challenges while ensuring fodder security for livestock. Further research into the long-term economic and social implications of changing fodder practices is essential for developing policies that balance the needs of rural communities with environmental sustainability.

Table 6. Relationship between key variables

Variables	Fodder availability	Collection time	Household income	Education level	Market distance
Fodder availability	1.00				
Collection time	-0.78***	1.00			
Household income	0.21*	-0.34**	1.00		
Commercial feed adoption	0.15	-0.28*	0.64***	0.48**	-0.53**
Cultivated fodder adoption	0.12	-0.31**	0.57***	0.45**	0.37*
Livestock numbers	0.43**	-0.39**	0.36*	0.17	-0.14

Note: All chi-square tests conducted with df = 1. Significance level set at $\alpha = 0.05$. Correlation coefficients are Pearson's r.

DISCUSSION

The findings of this study underscore the significant challenges faced by rural communities in Chamoli district, Uttarakhand. The decline in traditional fodder resources is influenced by multiple environmental and socioeconomic factors. The reduction in livestock numbers, the shift in fodder collection patterns, and the increasing reliance on alternative feed sources represent a complex interplay of ecological, economic, and cultural changes. One of the most striking findings of this study is the significant decline in fodder availability, with a mean reduction of 37% since 1990. This trend is particularly pronounced in higher altitude zones (>2500 m), where climate change-induced factors like reduced snowfall and altered precipitation patterns have had the most severe impact (Aryal et al. 2014). The results align with broader trends observed in the Himalayas, where changes in seasonal weather patterns have led to the degradation of alpine ecosystems, which are critical for the fodder supply in these regions (Sati 2015). Similarly, the middle and lower ecological zones have faced significant pressures from human activities, such as land conversion for agriculture and the proliferation of invasive species, highlighting the multi-dimensional threats to traditional fodder resources (Korner 2004). These findings suggest that each ecological zone experiences distinct, but interconnected, drivers of fodder scarcity. The variation in fodder availability across altitude zones supports the need for tailored management strategies that account for these differential impacts. The shift from forest-based and agricultural by-product fodder collection to alternative feed sources has led to increasing financial and physical burdens for rural households. The doubling of time spent on fodder collection, from 2.1 hours per day in 1990 to 4.3 hours per day in 2024, reflects the increased scarcity of traditional fodder sources and the need for greater mobility to gather feed (Katoch 2022). The geographical pattern of fodder collection, especially the longer distances traveled, suggests that rural households are increasingly forced to rely on distant grazing areas, adding a logistical burden to already strained resources. This phenomenon is not isolated to Chamoli but reflects global patterns where traditional subsistence practices are disrupted due to climate change and resource degradation. Furthermore, the extension of the period of acute fodder shortages from 2.3 months in 1990 to 4.7 months in 2024 highlights the growing vulnerability of rural communities, who now face longer periods of fodder insecurity for their livestock, exacerbating the economic stress faced by these households (Ahmed et al. 2018). The adoption of alternative fodder strategies further exemplifies the socioeconomic divides within the region. Wealthier households, with higher income and better access to markets, are more likely to invest in commercial feeds. In contrast, poorer households rely more on crop residues and purchased forest fodder, often the most accessible and cost-effective options. This divide is consistent with research indicating that the adoption of innovative farming practices, such as purchasing commercial feed or cultivating fodder, is typically constrained by economic resources (Ghimire et al. 2015; Dhakal et al. 2022).

Moreover, while the adoption of crop residues remains widespread across all economic groups, the differences in commercial feed and cultivated fodder use underscore the economic barriers to accessing sustainable fodder solutions. Household income, market access, and education level are critical determinants of the adoption of alternative fodder sources. These factors are consistent with findings

from other studies, which have emphasized the role of socioeconomic factors in shaping adaptation strategies to climate change and resource scarcity (Chettri et al. 2024). Specifically, the strong relationship between income and the adoption of commercial feed highlights the importance of economic capital in shaping rural resilience. Additionally, education emerged as a significant predictor of the adoption of both commercial feed and cultivated fodder. This suggests that knowledge and awareness of agricultural practices play a pivotal role in transitioning towards more sustainable fodder management systems (Bwalya et al. 2023; Tulu et al. 2023). Further, ecological changes influencing fodder availability and the fragmentation of forested areas and loss of dense forest are also reasons for this decline. This aligns with the findings of other studies (Kassa et al. 2017; Tripathy 2023), which have observed the encroachment of human settlements and infrastructure, such as roads, into traditionally forested areas, thereby limiting access to forest-based fodder. The fact that many villages are experiencing the most difficulty in accessing fodder is a critical finding and has been observed in various studies globally, such as Paterson et al. 1998; Maleko et al. 2018; Singh et al. 2022; and Dhamodharan et al. 2024. This highlights the tension between conservation goals and the livelihood needs of local communities globally. The economic implications of these changing fodder practices are significant. As households shift to purchasing commercial feeds, the economic burden on rural families has increased substantially, with annual fodder expenses rising. This increase in costs mirrors broader trends in agricultural economies where the growing reliance on external inputs increases household expenditure and reduces economic sustainability (Bist et al. 2024). The higher expenditure on fodder is particularly burdensome for economically disadvantaged households, where fodder-related costs account for a larger proportion of their total household expenditure. This disparity highlights the need for policies that address the financial constraints faced by these households while ensuring equitable access to sustainable fodder solutions. At the same time, the increased workload for women in fodder collection reflects broader socio-cultural dynamics. Women who traditionally bear the responsibility for livestock management are now spending more time on fodder collection (Maikhuri et al. 2011), which limits their ability to participate in other economic activities (Rocheleau 2019). This shift in gender dynamics could have long-term implications for women's empowerment and overall community well-being (Upadhyay 2005).

The findings of this study offer critical insights into the socioeconomic and ecological transformations occurring in the Chamoli district due to the decline of traditional fodder resources. The complex interaction between climate change, land use change, and socioeconomic factors has placed rural communities in a vulnerable position, with increasing pressure on both their time and financial resources. To address these challenges, it is essential to implement targeted policies that promote sustainable fodder management, improve market access, and provide educational and financial support to vulnerable households. Furthermore, future research should explore long-term solutions such as agroforestry, improved pasture management, and community-based resource management systems that can offer sustainable alternatives to the growing reliance on commercial feed and help safeguard the livelihoods of rural communities in the region.

CONCLUSION

The problems that mountain people face across the Himalayas are reflected in the Chamoli fodder crisis. Environmental degradation, shifting policies, and economic difficulties have altered the once-stable balance of forests, grasslands, and farms that provided enough feed for cattle. The adaptation process to changing fodder conditions is not uniform or equitable. Wealthier households have the option to cultivate fodder crops or purchase commercial feed. In order to cope, poorer households may accept reduced livestock output, reduce herds, or spend more time gathering limited supplies. Since the alternatives accessible to low-income families sometimes include degrading commons or abandoning livestock that have supported families for generations, this imbalance poses a danger of widening inequality and raising environmental problems. From a conservation perspective, people turn to alternatives when established sources do not work,

which might lead to new ecological stresses. Because of the close linkages between communities and forests, promoting sustainable fodder production serves both subsistence and conservation. Programs must recognize that fodder is linked to knowledge systems, economic opportunity, resource access, and land governance. These findings extend beyond Chamoli. They show how climate change, forest policies, and economic pressures combine to undermine traditional systems that have sustained Himalayan communities for generations. What is needed instead are approaches that strengthen community control over forests. These approaches must also make commercial inputs affordable for vulnerable households and value women's knowledge and time. In mountain areas, human well-being and ecosystem health cannot be separated. The goal should be sustaining not just livestock numbers but the social fabric and ecological foundations that make mountain life possible. ■

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LANDSLIDE SUSCEPTIBILITY PREDICTION ON MOUNT MARAPI USING INTERFEROMETRIC SYNTHETIC APERTURE RADAR (INSAR) INTEGRATED WITH MULTI-MODEL MACHINE LEARNING APPROACHES

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ABSTRACT. Landslides on Mount Marapi, West Sumatra, Indonesia, pose significant threats to human life, infrastructure, and the surrounding environment. This study examines patterns of surface deformation and predicts landslide susceptibility on Mount Marapi by integrating Interferometric Synthetic Aperture Radar (InSAR) interferograms with a multi-model machine-learning framework. Landslide susceptibility prediction was conducted using K-Nearest Neighbors (KNN), Random Forest (RF), Support Vector Machine (SVM), and Gradient Boosting (GB) algorithms. Integration of InSAR-derived deformation data with geospatial variables and machine learning facilitates a more comprehensive understanding of deformation dynamics and landslide susceptibility. The findings reveal a dominant trend of subsidence accompanied by persistent fluctuations along the mountain slopes, largely driven by recurrent landslides across multiple locations, thereby reshaping the surface morphology. InSAR data provide a spatially continuous representation of deformation within landslide-prone zones. Among the evaluated algorithms, RF demonstrated the highest predictive performance, yielding an accuracy of 94.33% and a precision of 91.30%. Key variables such as slope gradient, elevation, and rainfall emerged as the most influential determinants of landslide susceptibility. Additionally, seismic activity along the subduction zone and tectonic earthquakes act as further triggers, intensifying landslide occurrence in conjunction with extreme rainfall events. Although secondary factors such as curvature, soil type, and localized deformation exert relatively weaker influences, their interactions remain important in constructing a holistic landslide prediction framework. Overall, this study highlights the effectiveness of integrating InSAR with machine learning to advance multivariable approaches for forecasting and mitigating landslide hazards on Mount Marapi.

KEYWORDS: DInSAR, ground deformation, landslide, GeoAI, machine learning

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INTRODUCTION

Natural disasters, particularly landslides in mountainous regions, represent severe threats to human life, infrastructure, and ecosystems. Indonesia, located along the Pacific Ring of Fire, is highly prone to geological hazards, with volcanic activity constituting a major source of risk. Following the major eruption of Mount Marapi in December 2023, the surrounding area of West Sumatra experienced a subsequent disaster in May 2024: a landslide triggered by the volcano's geomorphic and

environmental conditions (Abu et al. 2021). Meteorological conditions, particularly intense rainfall, represent a primary triggering factor for landslide movements and cold lava floods, leading to severe damage, loss of life, and disruption of local livelihoods (Wulansari et al., 2024). The presence of unconsolidated volcanic deposits on steep, unstable slopes further amplifies susceptibility to mass movements during heavy precipitation events (Narny et al., 2025). In addition to hydrometeorological triggers, geophysical factors such as proximity to tectonic fault systems, seismic activity, and

variations in peak ground acceleration following earthquakes play a critical role in destabilizing the landscape, particularly in volcanic terrains (Le Breton et al. 2021). Despite the recurrence of landslides in the Mount Marapi region, comprehensive mapping and predictive modeling efforts remain limited. Addressing this gap is vital for understanding the complex interplay of geomorphic and geophysical processes in one of Indonesia's most tectonically and volcanically active regions, thereby improving disaster preparedness and risk mitigation strategies.

Synthetic Aperture Radar (SAR)-based active remote sensing, which employs microwave signals, has proven to be a highly effective tool for detecting and monitoring ground deformation associated with landslides and other mass-movement processes (Mondini et al. 2019). Particularly noteworthy is the use of Sentinel-1 time-series data processed through the LiCSAR automated system, which applies the Small Baseline Subset (SBAS) InSAR approach to generate detailed temporal and spatial information on surface deformation (Lazecky, 2020). Leveraging Interferometric Synthetic Aperture Radar (InSAR) techniques allows for the detection of subtle ground displacements with high precision, thereby facilitating the identification of precursory deformation in landslide-prone areas. This capability is critical for the early recognition of hazardous zones, as regions exhibiting prior deformation are considerably more susceptible to subsequent slope failures. Such geospatial intelligence plays a pivotal role in informing proactive disaster mitigation strategies, particularly within volcanic environments (Hanif et al., 2024a).

Advancements in machine learning (ML) applied to geospatial data, commonly referred to as Geo-Artificial Intelligence (GeoAI) has introduced transformative opportunities for natural hazard prediction and risk reduction (Demertzis et al. 2021). GeoAI represents an interdisciplinary domain that integrates artificial intelligence (AI), geographic information systems (GIS), and geospatial science to intelligently analyze, model, and interpret complex spatial datasets. By employing AI methodologies such as machine learning, deep learning, and neural networks, GeoAI enables the efficient processing of large-scale geospatial data, facilitating the extraction of meaningful patterns and actionable insights (Lu et al. 2025).

The application of GeoAI in disaster studies, particularly landslide prediction, has demonstrated significant potential. Machine learning algorithms are well-suited for analyzing multidimensional spatial datasets, detecting nonlinear relationships, and producing robust forecasts of hazardous

events. Within the context of landslide risk assessment, ML-based models substantially improve predictive accuracy, thereby supporting the delineation of high-risk zones. This capability is critical for informing proactive disaster mitigation strategies and enhancing resilience in vulnerable regions (Mao et al. 2024).

The present study addresses the research gap in post-eruption landslide analysis in volcanic environments by integrating remote sensing and machine learning approaches to systematically map and predict landslides in volcanic terrains. Beyond advancing scientific understanding, this research provides practical value for disaster risk governance by delivering evidence-based insights that strengthen early warning systems and guide policy interventions. Moreover, the study contributes to the broader geoscientific discourse on landslide dynamics in volcanic landscapes, offering a methodological framework applicable to other disaster-prone regions.

The objectives of this study are to analyze volcano surface deformation patterns at landslide event locations from 2020 to 2024 and to integrate deformation data with diverse spatial datasets and machine learning for predicting areas susceptible to landslides. By combining remote sensing technologies with advanced data-driven modeling approaches, this research contributes to disaster risk reduction in volcanic environments. The findings are expected to support the strengthening of local community resilience and the mitigation of socio-environmental impacts arising from future geological hazards in the Mount Marapi region.

MATERIALS AND METHODS

Sampling Location

Mount Marapi, located in West Sumatra, is recognized as the most active volcano on the island of Sumatra. Its name, which translates to "*Mountain of Fire*", aptly reflects its persistent volcanic activity. Rising to an elevation of 2,891 meters above sea level, Marapi is characterized by explosive eruptions that generate violent blasts of pyroclastic material, volcanic ash, and lava flows. From a geological perspective, the volcano is positioned along the Semangko Fault, a major tectonic structure within the Sunda subduction zone, extending from the Sianok Valley to Lake Singkarak (Fig. 1). Administratively, Mount Marapi lies within two regencies, Agam Regency and Tanah Datar Regency, under the jurisdiction of West Sumatra Province.

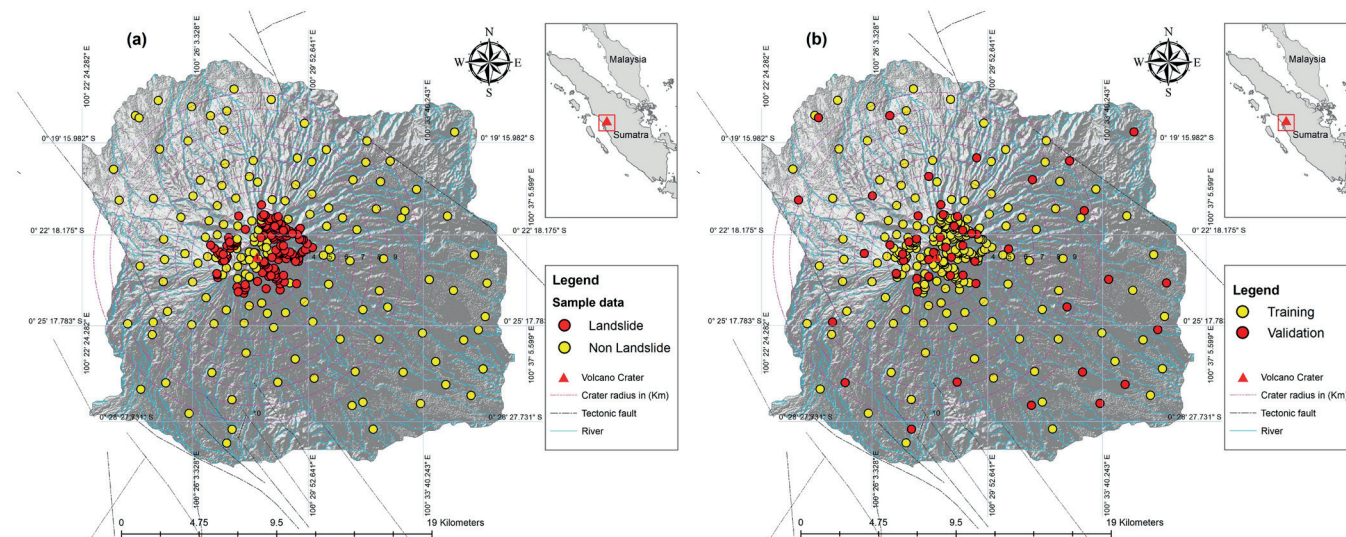


Fig. 1. (a) Distribution of landslide and non-landslide data, and (b) distribution of training and validation data in the study area at Marapi Volcano, West Sumatra, Indonesia

In this study, historical landslide occurrence points from 2020 to 2024 were compiled through on-screen digitization of high-resolution satellite imagery inventories using Google Earth. To establish a balanced dataset, an equal number of non-landslide points were randomly sampled from areas with no recorded landslide activity. Each landslide point was assigned a class value of 1, while non-landslide points were assigned a class value of 0. A total of 294 sample data points were compiled, with a 50/50 ratio of points labeled as landslides and non-landslides. These labeled points were subsequently used as reference data for training and validating the machine learning-based landslide prediction models, which were divided into training and validation sets in a 70/30 ratio.

Material

This study employs multiple open-access datasets, which were systematically integrated and processed into derivative products tailored to the analytical requirements. All data were obtained from official provider platforms, ensuring reliability and reproducibility. The datasets and their corresponding information are summarized in Table 1. To maintain consistency and facilitate spatial comparability, all raster datasets were resampled to a standardized spatial resolution of 50 meters.

Data preprocessing for the variable analysis was conducted using an integrated GIS and remote sensing framework. Land-cover classification was implemented through supervised classification techniques, while terrain characteristics were derived from Google Earth Engine. Earthquake density, gravity anomalies, and river density were quantified using kernel density estimation.

InSAR for Surface Deformation Monitoring

Sentinel-1 Synthetic Aperture Radar (SAR) data were processed using the LiCSAR (LiCS Automated Processing System) platform to generate Interferometric Synthetic Aperture Radar (InSAR) products. The data used are of descending type with temporal recording. LiCSAR processing includes multiple stages such as burst extraction, frame compilation, and image coregistration, incorporating spectral diversity correction and other essential adjustments

(Lazecky, 2020). To address decorrelation in low-coherence areas, LiCSAR applies several techniques, including spatial and temporal filtering, multi-interferogram stacking, and advanced approaches such as Persistent Scatterer InSAR (PS-InSAR) and Small Baseline Subset (SBAS). In particular, SBAS time-series interferograms are generated through a small-baseline strategy and subsequently refined via iterative decomposition (Morishita, 2020).

For the detailed assessment of surface deformation at landslide locations, unwrapped phase time-series data were extracted from the InSAR products. Statistical analyses were then performed for each landslide sample point, including temporal trend evaluation, calculation of maximum and minimum displacement values, and deviation analysis. These deformation metrics provide critical insights into the spatial and temporal variability of displacement processes in landslide-prone areas, thereby enhancing the understanding of slope instability dynamics.

Machine Learning for Predicting Landslide Susceptibility

This study employs a multi-model machine learning framework based on supervised learning algorithms. The models operate as binary classifiers, requiring labeled training data in which a value of “1” denotes the presence of a landslide and “0” indicates its absence. Such labeled datasets allow the algorithms to recognize patterns and establish predictive relationships between input variables and landslide occurrences. To ensure a fair and objective comparison among the algorithms employed in this study, the hyperparameters of each machine learning model were systematically tuned to obtain their respective optimal configurations. The selected optimal parameters are then applied to the algorithms implemented in this study.

The selected machine learning algorithms are capable of producing both classification and regression outputs, depending on the predictive objective. While each algorithm applies distinct computational strategies, together they capture complex non-linear interactions among variables. In comparison with conventional statistical techniques, machine learning methods exhibit greater capacity to manage high-dimensional geospatial datasets and achieve higher predictive accuracy (Wu et al. 2024). The models implemented in this study include:

Table 1. Dataset of predictor variables for landslide susceptibility analysis

Data	Required information for predictor variables	Data Sources
Sentinel 1	(1) Surface deformation	https://comet.nerc.ac.uk/COMET-LiCS-portal/
Sentinel 2	(2) Land cover	https://www.copernicus.eu/en
Land systems	(3) Soil type	https://inaland.big.go.id/map
SRTM	(4) Elevation, (5) slope, (6) curvature, (7) river density	https://earthexplorer.usgs.gov/
Earthquake	(8) Earthquake density	https://earthquake.usgs.gov/earthquakes/search/
Seismic Hazard Map	(9) Peak Ground Acceleration (PGA)	https://www.globalquakemodel.org/product/global-seismic-hazard-map
Geology	(10) Geology, (11) distance to tectonic fault	https://geologi.esdm.go.id/geomap
Gravitation	(12) Gravitation	https://bgi.obs-mip.fr/
CHIRPS	(13) Precipitation	https://www.chc.ucsb.edu/data/chirps

• K-Nearest Neighbors (KNN)

The K-Nearest Neighbors (KNN) algorithm classifies data points according to the majority class among their nearest neighbors, where the model determines neighborhood proximity by measuring the distance between a test sample and the corresponding training samples (Su et al. 2024). The KNN method functions as a non-parametric algorithm because it does not assume any predefined statistical distribution of the input data. This property allows the algorithm to adapt effectively to a wide range of geographic datasets with heterogeneous characteristics (Adnan et al. 2020). However, the performance of the KNN algorithm depends strongly on the selection of the parameter k and on the appropriate scaling of the input features. In addition, the computational cost of the algorithm increases substantially as the size of the dataset grows because the model must evaluate distances between the prediction sample and all training observations (Xia et al. 2017). Before the model performs predictions on the complete dataset, the study conducts a hyperparameter tuning procedure to identify the optimal configuration of the algorithm. The tuning process determines that the most suitable parameters for the model include the Euclidean distance metric, a value of k ($n_neighbors$) equal to 9, a p parameter value of 1, and a distance-based weighting scheme.

• Random Forest (RF)

The Random Forest (RF) algorithm employs a bagging strategy by constructing multiple Decision Tree classifiers on randomly selected subsets of the dataset and subsequently aggregating their predictions to produce a more robust final output. This ensemble learning approach reduces model variance, improves generalization performance, and enhances classification stability compared with the use of a single decision tree model (Li et al. 2024). In addition, the RF algorithm can effectively handle datasets containing a large number of variables and can provide valuable analytical insights through feature importance ranking, which is particularly beneficial when analyzing complex geospatial datasets (Chowdhury et al. 2024). However, the interpretation of aggregated predictions from the RF model is often less straightforward than the interpretation of a single decision tree structure (Wen et al. 2024). In this study, a hyperparameter tuning procedure was conducted to determine the optimal configuration of the RF model. The tuning process identified the following parameter settings as optimal: $n_estimators = 400$, $min_samples_split = 10$, $min_samples_leaf = 5$, $max_features = \log_2$, $max_depth = \text{None}$, and $bootstrap = \text{True}$. These optimized parameters were subsequently applied to train the model and perform predictions across the entire dataset used in this research.

• Support Vector Machine (SVM)

The Support Vector Machine (SVM) operates by constructing an optimal hyperplane that maximizes the margin separating data points belonging to different classes. The SVM model possesses a major advantage in its ability to address both linear and non-linear classification problems through the application of kernel functions. This capability makes the model particularly suitable for complex classification tasks involving spatial datasets (Huang et al. 2022). The SVM also demonstrates strong performance when handling high-dimensional datasets because the algorithm focuses on the most informative boundary samples, commonly referred to as support

vectors (Xu et al. 2024). However, the effectiveness of the model remains highly sensitive to the selection of hyperparameters, and the computational cost can increase substantially when the algorithm is applied to large-scale datasets (Xia et al. 2017). In this study, the SVM model was trained prior to full implementation through a hyperparameter tuning procedure designed to identify the most suitable parameter configuration. The tuning results indicated that the optimal model configuration uses a sigmoid kernel, a gamma value of 0.1, and a regularization parameter (C) equal to 1. The study subsequently applied this optimized configuration to perform classification across the entire dataset used in this research.

• Gradient Boosting (GB)

The Gradient Boosting method represents an ensemble learning technique that constructs predictive models sequentially, where each subsequent model is trained to correct the residual errors generated by the preceding iteration. This learning strategy enables the model to gradually improve prediction performance by minimizing the remaining error at each stage of the training process (Kavzoglu and Teke, 2022). The Gradient Boosting approach is frequently applied to natural hazard prediction problems, including landslide susceptibility analysis (Zhang et al. 2022). In most implementations, the algorithm employs shallow Decision Tree structures as weak learners, allowing the ensemble model to incrementally enhance predictive accuracy through iterative error reduction (Sahin, 2022). Although the method is highly effective in capturing complex nonlinear relationships within datasets, the model requires careful hyperparameter tuning because excessive iterations or overly deep trees can increase the risk of overfitting (Sahin, 2022).

In this study, a hyperparameter tuning procedure was conducted to determine the most appropriate configuration of the Gradient Boosting model for the research dataset. The tuning results identified the following optimal parameter settings: $subsample = 0.7$, $n_estimators = 100$, $min_samples_split = 10$, $min_samples_leaf = 4$, $max_depth = 2$, and $learning_rate = 0.1$. The study subsequently applied this optimized configuration to train the model and perform predictive analysis on the dataset used in this research.

A multi-model machine learning framework was implemented by partitioning the dataset into training and testing subsets according to a predefined ratio (Abu et al. 2021), thereby reducing the risk of overfitting (see Fig. 1). Landslide prediction requires two principal datasets: (i) historical records of landslide events as a label dataset and (ii) predictor variable data. In this study, 13 predictor variables were selected (see Table 1).

Model performance was evaluated using multiple statistical metrics, including test accuracy, recall, F1-score, and Rate of Change (ROC) to ensure robust and reliable prediction outcomes. During the data exploration phase, correlation analysis was conducted to examine the interrelationships among variables, thereby identifying potential dependencies and assessing how variations in one factor may influence others. Furthermore, variable importance analysis was performed to quantify the contribution of each factor to landslide susceptibility, highlighting the most influential predictors for landslide occurrence in the Mount Marapi region. This step enhances the interpretability of the models and strengthens their predictive capability.

RESULTS

Trend surface ground deformation on the landslide

The results derived from InSAR time-series analysis, covering a five-year observation period, reveal distinct deformation patterns at landslide-prone locations based on the annual average deformation values (Table 2). Overall, deformation activity in the Mount Marapi region exhibited a declining trend between 2020 and 2024, although intermittent fluctuations with localized increases were still detected during certain intervals. The maximum annual deformation ranged from 53.70 mm in 2023 to 110.95 mm in 2022, with a five-year average of 79.30 mm. Conversely, the minimum deformation values ranged from -67.19 mm in 2021 to -157.58 mm in 2020, yielding an overall average of -74.42 mm across the study period. Meanwhile, the mean annual deformation values varied from 9.11 mm in 2024 to 20.64 mm in 2020, reflecting temporal variability in slope displacement intensity.

The deformation trend in the Mount Marapi region demonstrates a progressive decline in maximum deformation, decreasing from 110.95 mm in 2022 to 56.07 mm in 2024, thereby indicating a reduction in the intensity of surface displacement processes. In contrast, the minimum deformation values exhibit irregular fluctuations,

with pronounced negative displacements of -67.19 mm in 2021 and -61.93 mm in 2023, reflecting localized subsidence phenomena. The standard deviation of the deformation data ranges from -36.13 mm to 14.48 mm, underscoring considerable temporal variability in ground movement. Notably, 2022 recorded the greatest variability, with a standard deviation of 14.48 mm, suggesting that deformation activity during this year was more spatially and temporally heterogeneous compared to other periods.

Spatial variations in the average deformation distribution over the five-year observation period are clearly discernible. Areas represented in red on the deformation map exhibit maximum uplift of up to 32.8 mm, whereas zones characterized by blue signatures indicate subsidence, with minimum values reaching -34.9 mm. Distinct spatial patterns emerge, particularly across the transitional zones between sloping and steep terrains extending toward the mountain summit. In contrast, the lowland plains at the mountain's base display comparatively moderate deformation values ranging from -17.9 mm to 15.9 mm, represented by a gradient of blue to orange hues (Fig. 2). This spatiotemporal deformation pattern constitutes a critical parameter for landslide susceptibility assessment in the Mount Marapi region. Furthermore, annual deformation data were systematically extracted for all recorded landslide events, as presented in Table 3.

Table 2. Annual deformation based on InSAR time series for Mount Marapi

Surface deformation (mm/ year)						
Years	2020	2021	2022	2023	2024	Average
Max Deformation	86.68	89.10	110.95	53.70	56.07	79.30
Min Deformation	-157.58	-67.19	-42.17	-61.93	-43.24	-74.42
Yearly Average	20.64	13.13	11.28	10.46	9.11	12.92
Stdv	-36.13	-5.59	14.48	-9.96	2.04	-7.03

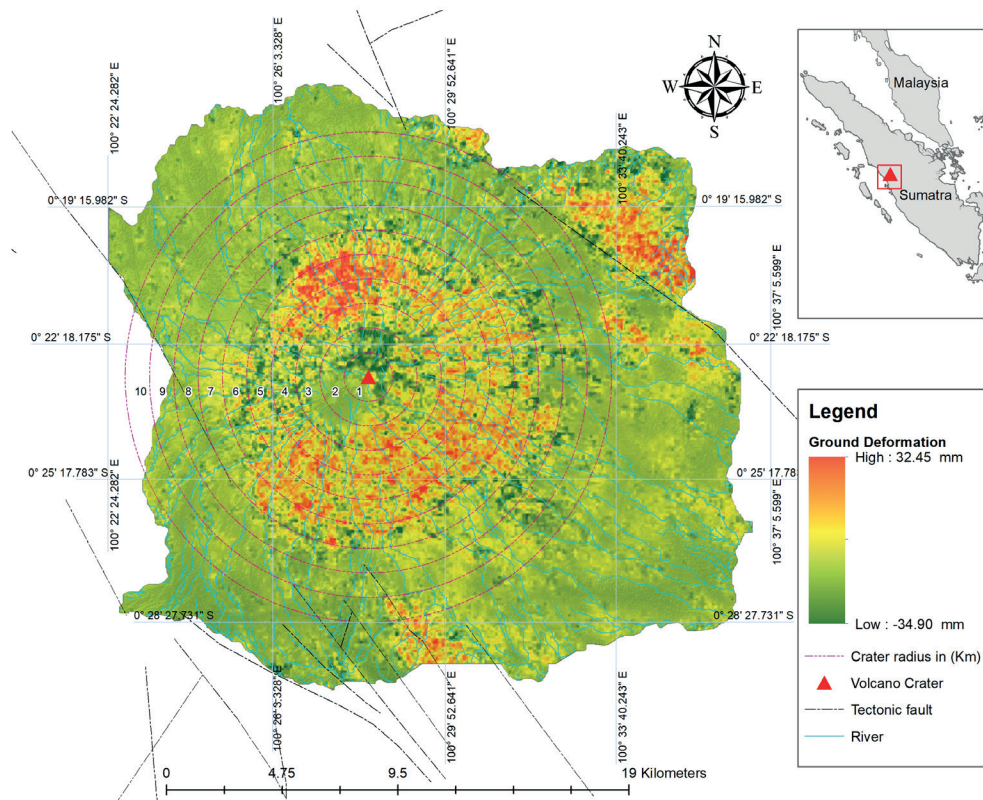


Fig. 2. Average annual deformation from 2020 to 2024

Table 3. Annual InSAR deformation at landslide occurrence points

Yearly deformation (mm/year)						
Years	2020	2021	2022	2023	2024	Average
Max Deformation	23.88	42.95	58.47	27.33	43.56	39.24
Min Deformation	-109.34	-36.72	24.51	34.27	-17.00	-44.37
Yearly Average	-51.19	0.71	12.16	-9.16	9.32	-7.63
Stdv	28.81	15.23	14.93	12.87	10.37	16.44

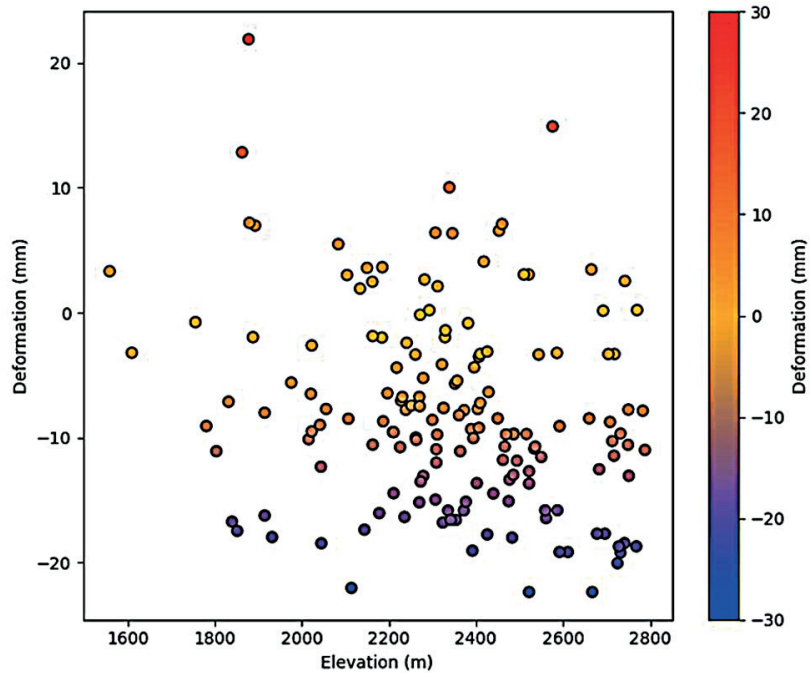


Fig. 3. Average annual deformation vs. elevation of each landslide point

Overall, all identified landslide sites exhibited indications of ground subsidence, with the average annual deformation showing negative displacement values (Fig. 3). Several locations recorded deformation values approaching -20 mm per year, which indicates persistent and periodic ground surface movement throughout the observation period of the deformation analysis. This sustained subsidence pattern suggests progressive slope instability that may culminate in peak subsidence events manifested as hillside collapse.

Landslide Susceptibility Zones

To predict landslides in the Mount Marapi area, a set of thematic spatial datasets is utilized, each representing factors that are interrelated and contribute to landslide susceptibility. The correlation matrix between these variables serves as a statistical tool to evaluate the strength and direction of their relationships, with correlation values ranging from -1 to 1 . In this study, several key correlations were identified. Elevation exhibits a positive correlation with slope, river density, tectonic distance, and earthquake density, while showing a significant negative correlation with precipitation and land cover. Similarly, slope is positively correlated with elevation, river density, tectonic distance, and earthquake density, but negatively correlated with precipitation and land cover. River density also demonstrates positive correlations with elevation and slope but is negatively correlated with precipitation (See Fig 4). (Fig. 4).

From the correlation matrix, it can be inferred that precipitation exhibits a strong negative correlation with nearly all other variables, suggesting that higher rainfall is generally associated with lower values of factors such as elevation, slope, and related parameters. In contrast, both elevation and slope demonstrate significant positive correlations with variables including river density, tectonic distance, and earthquake density, indicating that topographic conditions may exert a considerable influence on these geomorphological and tectonic factors.

Each variable incorporated into the landslide prediction model contributes a distinct percentage to the overall predictive performance (see Fig. 5). Among these, three variables play a dominant role: slope, elevation, and precipitation. Slope emerges as the most influential factor, accounting for 37.99%, underscoring its critical role in determining landslide susceptibility in the Mount Marapi region. Elevation follows with a contribution of 17.28%, reflecting the influence of terrain height on soil stability and landslide potential, particularly within rugged and mountainous landscapes. Precipitation, contributing 13.76%, highlights the importance of rainfall as a triggering factor, where intense precipitation in upstream areas, especially on steep slopes, enhances soil saturation and markedly increases the likelihood of slope failure.

Other variables also demonstrate noteworthy contributions. Land cover accounts for 7.74%, indicating that vegetation type and land use significantly influence slope stability. Proximity to tectonic faults (5.92%) and

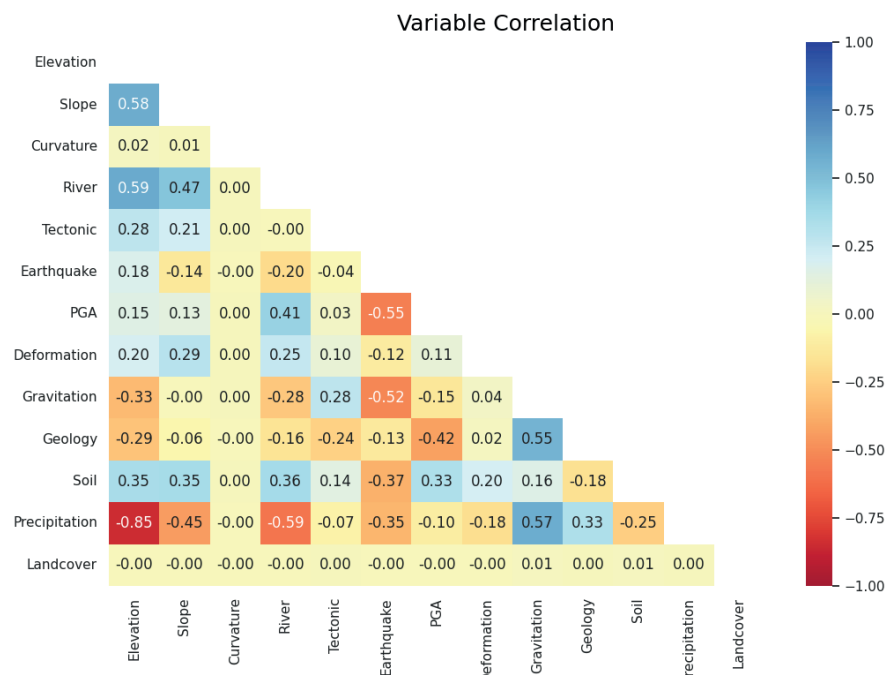


Fig. 4. The variable correlation for landslide prediction %

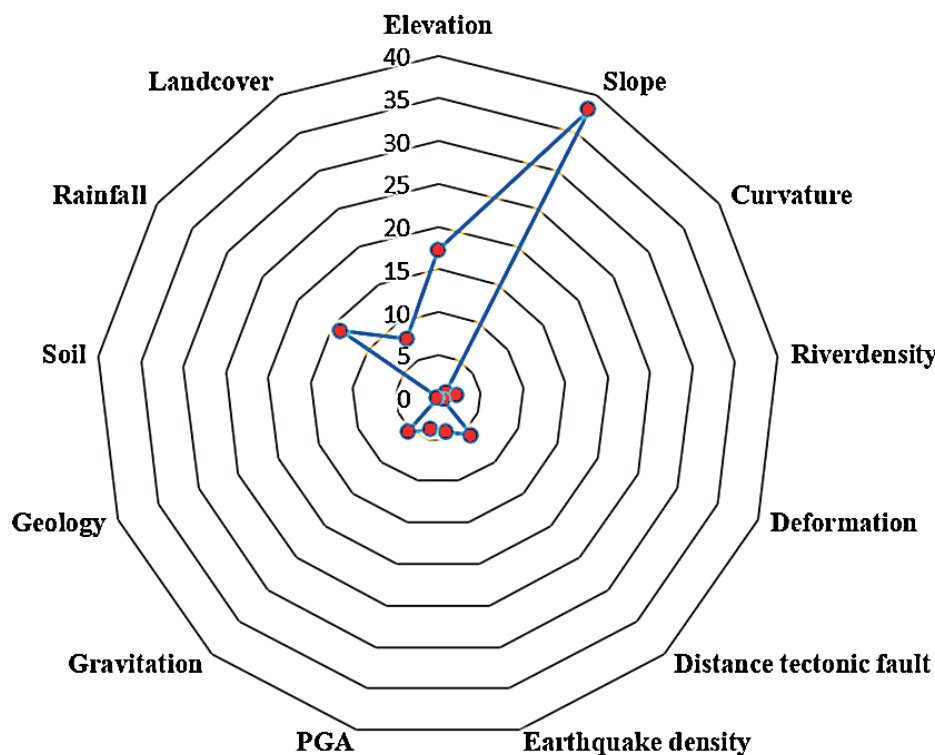


Fig. 5. The variable importance of landslide prediction in (%)

gravity-related factors (5.30%) further emphasize the role of geological activity and gravitational forces in slope instability. While variables such as land cover, tectonic fault distance, and gravity exert moderate effects, factors including curvature, ground deformation, and soil properties contribute minimally. Nevertheless, these parameters remain important in comprehensive landslide prediction analyses, as their combined interactions may still influence landslide occurrence.

After determining the optimal parameter configuration, the tuned parameters were subsequently applied to all machine learning algorithms implemented in this study, as summarized in the following Table 4. The predictive modeling results obtained through KNN, RF, SVM, and GB effectively delineated zones of potential landslide

occurrence, assigning probability values ranging from 0 to 1. A value approaching 1 indicates a higher likelihood of landslide occurrence, thus providing a probabilistic basis for identifying and prioritizing high-risk areas (Fig. 6).

A performance comparison of multiple machine learning models based on various evaluation metrics is presented in Table 4. The models tested for landslide hazard prediction include KNN, RF, SVM, and GB. Among these, the Random Forest model demonstrated the highest overall performance, achieving an accuracy of 94.33% and a precision of 91.30%. These results indicate that Random Forest provides superior predictive accuracy with substantially lower error rates compared to the other models. KNN reached an accuracy of 92.45% and a precision of 84.61%. The Support Vector Classifier showed

Table 4. Model performance for landslide prediction

Multi-Machine Learning Approach	Accuracy %	Precision %	F1-Score	Recall	ROC
K-Nearest Neighbors	92.45	84.61	0.91	1	0.99
Random Forest	94.33	91.30	0.93	0.95	0.97
Support Vector Classifier	88.67	90.00	0.85	0.81	0.93
Gradient Boosting	90.56	90.47	0.88	0.86	0.97

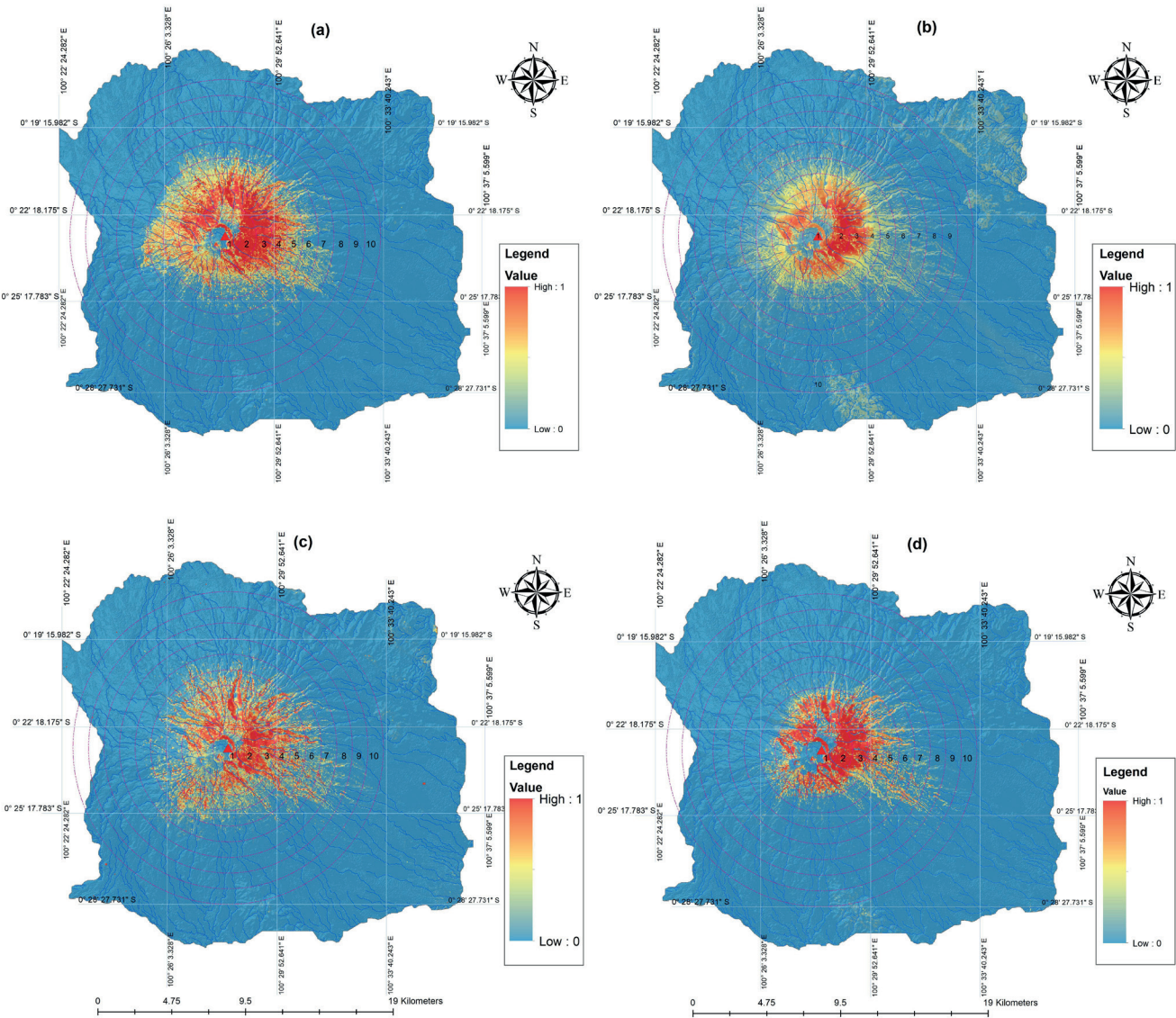


Fig. 6. The landslide probability around Mount Marapi: (a) K-Nearest Neighbors, (b) Random Forest, (c) Support Vector Classifier, and (d) Gradient Boosting.

the lowest predictive performance, further confirming its limited effectiveness for landslide prediction in the Mount Marapi region. The final landslide hazard prediction results generated by the Random Forest model are illustrated in Fig. 7.

Overall, the Mount Marapi region exhibits a higher probability of landslides in areas with steep slopes and elevated terrain, while relatively flat regions display a lower likelihood of occurrence. This spatial distribution delineates a hazard zone concentrated around the mountain's peak, suggesting that future landslides are likely to occur on multiple flanks of the volcano. The high-risk areas are characterized by elevated probability values compared to the lower foothill regions. This concentration of hazards near the peak is strongly correlated with the distribution of past landslide events, with 141 recorded incidents predominantly occurring on steep slopes and at higher elevations. In contrast, no landslide events have been documented in the foothill regions, where slopes are generally gentle or flat. The integration of landslide and non-landslide occurrence points plays a critical role in defining the spatial pattern of predicted susceptibility, as it directly influences the classification of spatial data across all contributing variables used in the analysis.

DISCUSSION

Deformation activity across the Mount Marapi region has generally exhibited a declining trend, although intermittent increases have been detected. On average, this indicates a net reduction in the mountain's surface elevation. This pattern is further corroborated by the progressive decrease in inflation rates, while deflation remains irregular and inconsistent, suggesting ongoing subsidence along the mountain slopes. The spatial distribution of deformation demonstrates a distinct configuration: moderate to steep slopes in proximity to the summit exhibit elevated inflation values, whereas the relatively flat foothill areas experience more stable and gradual deformation fluctuations. These displacement

dynamics are strongly governed by geological processes, volcanic activity, and environmental factors (Seropian et al. 2021). Moreover, the accumulation of volcanic deposits and erosional processes further complicate the vertical deformation regime.

The high sensitivity and precision of Synthetic Aperture Radar (SAR) technology enable deformation mapping with millimeter-level accuracy (Hanif et al. 2024b). Time-series deformation analysis at landslide-prone zones of Mount Marapi reveals considerable fluctuations, with a gradual attenuation of peak inflation values. The persistence of surface deformation indicates the contribution of internal volcanic processes such as eruptive activity, hydrothermal pressure, and volcanic seismicity to ground instability (Hendra et al., 2019). Volcanic activity plays a critical role in destabilizing slopes, enhancing rock instability, particularly in steep terrains (Heap et al., 2021; Hanif et al. 2024c). The observed reduction in deformation values is also attributed to landslide events in several sectors, which substantially modify the mountain's surface morphology (Lu et al. 2024).

InSAR data derived from the LiCSAR platform provides a detailed characterization of these deformation patterns, offering valuable insights for landslide prediction. The integration of LiCSAR-derived deformation measurements with landslide susceptibility models substantially strengthens hazard assessments. Deformation data functions as a crucial explanatory variable, capturing land surface dynamics that directly influence slope stability. Areas experiencing pronounced subsidence or localized uplift can thus be delineated as potential high-risk zones.

By integrating ground deformation data with additional predictive variables, a highly accurate landslide hazard map of Mount Marapi has been developed. Among the factors influencing landslide susceptibility within the Random Forest framework, slope, elevation, and precipitation exert the strongest control. Steep topography in high-elevation zones near the crater, combined with episodes of intense rainfall, markedly elevates the probability of slope failure. Mount Marapi's tropical montane environment further amplifies this susceptibility: dense forest cover,

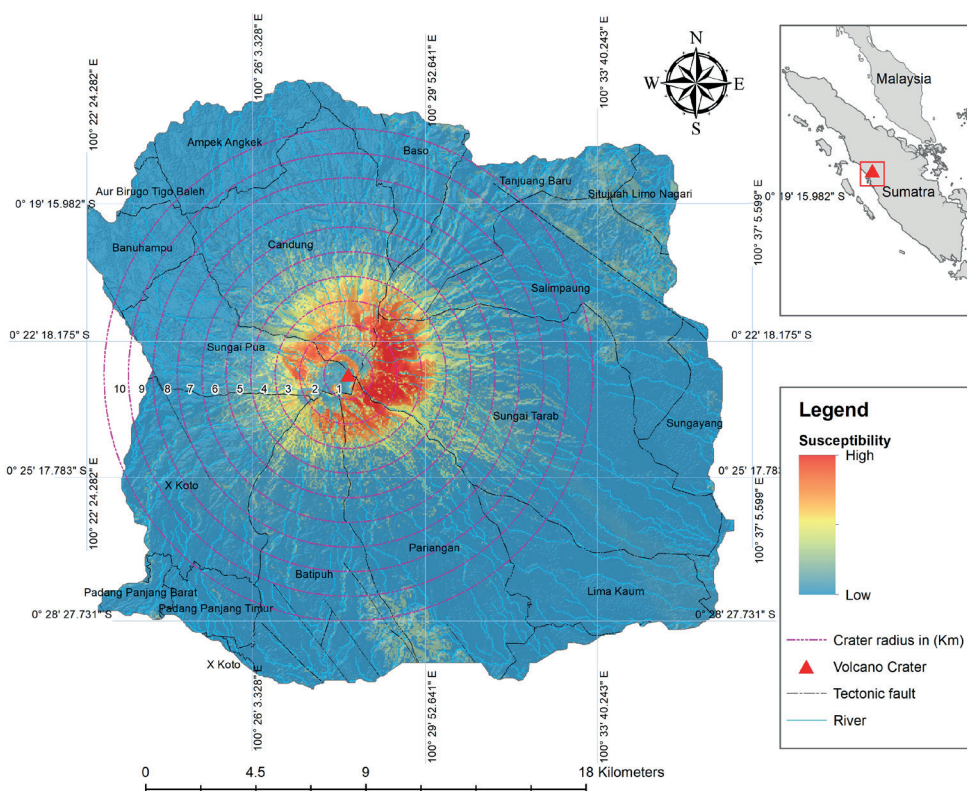


Fig. 7. The landslide susceptibility on Mount Marapi

high atmospheric humidity, and abundant precipitation, coupled with a relatively thin soil mantle overlying young volcanic deposits, predispose slopes to rapid soil saturation. The interplay of geomorphological, geological, and environmental variables collectively exacerbates slope instability, as these processes are interdependent and act synergistically to intensify landslide risk (Hussain et al. 2022; Tehrainsi et al. 2022).

Ground deformation signals derived from InSAR are strongly correlated with historical landslide events on Mount Marapi. Localized deformation on steep slopes, particularly in sectors experiencing uplift (inflation) or subsidence, contributes directly to terrain instability. Inflation increases internal stress within the volcanic edifice, whereas subsidence produces compaction and surface fissures, both of which promote mass movement. These processes are further accelerated under conditions of heavy rainfall, as infiltration elevates pore-water pressure and reduces soil shear strength, thereby heightening the likelihood of slope failure.

Among the various machine learning models applied for landslide prediction in the Mount Marapi region, the RF algorithm demonstrated superior performance in handling the spatial datasets, which consist of complex combinations of categorical and continuous variables. The RF model effectively delineated landslide susceptibility zones in an area with a documented history of landslide occurrences. This superiority arises from the ability of decision trees to capture non-linear relationships and construct intricate decision boundaries without relying on distributional assumptions (Li et al. 2024). Furthermore, the ensemble nature of RF, which aggregates multiple trees trained on randomized subsets of data and predictor variables, enhances model stability, reduces sensitivity to noise, and captures variable interactions more effectively, thereby producing results that are both accurate and generalizable (Lu et al. 2024).

The spatial distribution demonstrates a strong correlation between historical landslide occurrences and predictions generated by the RF model. Landslide events in mountainous terrain are not randomly distributed but instead form clusters on steep slopes at higher elevations, particularly around mountain peaks. This distribution corresponds with key controlling factors such as slope gradient, intense rainfall, and young volcanic lithology, which are spatially concentrated in specific zones. The Random Forest predictions reproduce this clustering tendency, with high probabilities of landslides along the mountain flanks and low probabilities across flatter terrain at the mountain base, thereby reinforcing confidence in the model's reliability. Nevertheless, as noted by Wen et al. (2024), strong spatial autocorrelation introduces the risk of spatial bias, whereby the model may become overly dependent on clustered historical patterns. As a result, although effective in identifying susceptibility zones resembling past events, the model may exhibit reduced sensitivity in detecting newly emerging vulnerable areas outside established clusters (Kanwar et al. 2025).

Furthermore, the results of landslide susceptibility zoning are strongly influenced by multiple factors, particularly Mount Marapi's tectonic position within an active subduction zone, which makes the region highly prone to seismic disturbances and highlights the importance of geologically based hazard assessment. Several geophysical conditions shape landslide dynamics in the area, including active tectonic plate convergence, seismic history, peak ground acceleration, and geomagnetic variations. The Semangko Fault, an active strike-slip

system undergoing continuous displacement, generates vertical and lateral deformation that frequently triggers tectonic earthquakes. Seismic shaking from these events reduces slope shear resistance and destabilizes surface materials, with its magnitude commonly quantified by peak ground acceleration (Chen et al. 2011; Xie et al. 2022). When coupled with intense rainfall, this seismic instability creates critical conditions for slope failure, particularly in steep and saturated terrains (Huang et al. 2024). Although secondary factors such as curvature, deformation rate, and soil composition exert relatively weaker direct effects, their cumulative and interdependent roles underscore the necessity of integrating them into a comprehensive, multi-variable landslide prediction framework.

The RF model produced accurate predictions; several biases may limit its reliability. Spatial bias arises because landslide events around Mount Marapi are concentrated in specific areas, while temporal bias reflects the restricted availability of historical inventories and the omission of extreme rainfall periods. Such limitations highlight that general computational principles cannot be directly applied to spatial data that represent real-world Earth surface processes, where geomorphic processes are highly context-dependent. For instance, steep slopes under intense rainfall are highly susceptible to landslides, whereas flat terrain may instead experience flooding due to poor drainage. This suggests that landslide prediction cannot rely solely on numerical or machine learning approaches (Chandran and Roy, 2024). A more robust framework requires integrating computational methods with fundamental geographical perspectives, drawing on spatial, environmental, and regional approaches for spatial data interpretation.

CONCLUSIONS

Deformation analysis using InSAR and landslide prediction through machine learning models provide complementary perspectives on land surface dynamics at Mount Marapi. The deformation trend indicates a gradual decline accompanied by periodic fluctuations, characterized by decreasing inflation rates and irregular deflation patterns, particularly along steep slopes near the summit. These deformation signals are primarily governed by volcanic activity, hydrothermal pressurization, and seismic events, all of which progressively destabilize rock masses and increase the likelihood of slope failure.

The application of ensemble and multi-machine learning approaches has further enhanced the predictive performance of landslide susceptibility models, with the Random Forest algorithm demonstrating the highest classification accuracy. Landslide occurrence is predominantly controlled by three critical factors: slope gradient, elevation, and rainfall intensity. High-altitude, steeply inclined slopes are especially vulnerable, particularly during periods of heavy precipitation. Tropical humidity, combined with thin soil layers, further amplifies instability, while seismic activity acts as a compounding trigger for slope failure. Additional conditioning factors including slope curvature, surface deformation anomalies, and soil type exert more subtle, yet still significant, influences on model predictions.

Deformation measurements capture surface displacements that directly affect slope stability, whereas machine learning-based prediction models delineate areas with heightened susceptibility to landslides. A holistic, integrated framework that synthesizes deformation monitoring with machine learning-based susceptibility

mapping is therefore essential for comprehensive hazard assessment and effective risk mitigation. Importantly, the landslide prediction framework employed in this study is based on open-source datasets, underscoring its scalability and potential applicability to diverse geomorphic and volcanic environments worldwide.

Despite its contributions, this research is subject to several limitations. The spatial resolution of DInSAR data from LiCSAR constrains its ability to detect small-scale deformation, particularly in areas with dense vegetation cover and steep topography. Second, the modeling framework incorporates a limited set of variables, which may not fully capture the complexity of field conditions.

In addition, the predictive models rely heavily on historical landslide inventories and satellite-derived rainfall data, the latter of which may underrepresent localized extreme precipitation events that act as critical landslide triggers. Another important limitation lies in the potential overestimation of model accuracy due to the absence of extensive field validation, combined with the inherently static nature of the model, which does not account for rapidly evolving geomorphological processes. For these reasons, the prediction outputs should be interpreted with caution, particularly in highly dynamic volcanic and mountainous environments where slope stability conditions can change abruptly. ■

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CHANGES IN THE CHEMICAL COMPOSITION OF WATER IN THE SMALL LAKE VENDYURSKOE (SOUTHERN KARELIA, RUSSIA) OVER 50 YEARS DUE TO CLIMATE CHANGE AND ANTROPOGENIC IMPACT

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ABSTRACT. Studies of changes in the chemical composition of lake water due to climate variability and human impact are highly relevant for Karelia, which has more than 60,000 lakes. Lake Vendyurskoe, a typical small lake in Karelia, has been used for growing rainbow trout since 2009. In the 1970–90s, drainage and logging were practiced in the catchment of this lake. A change in the composition of major ions in the lake's water and an increase in the labile component of organic matter were observed between 1971 and 2023. In 2021–2023, the concentration of sulfate ions decreased fourfold compared to 1971–1985, which may be due to both the cessation of drainage operations and a reduction in the concentration of sulfates in precipitation. Chloride ion concentrations were reduced by half. The 50-year decrease in bicarbonate concentrations was likely associated with increased precipitation. Total phosphorus concentrations in the lake water showed an upward trend over the 50 years (in both surface and bottom layers), indicating increased anthropogenic impact on the lake. During the summer stratification period, hypoxia develops in the deep-water parts of the lake and near trout cages, and phosphate concentrations in the bottom layers are quite high (up to 36 µg/L). The mobilization of phosphorus from bottom sediments under anoxic conditions creates a secondary phosphorus load, which may be the reason for the increased bioproductivity. A direct correlation was found between the duration of near-bottom hypoxia in summer and the average air temperature over the three summer months ($R^2 = 0.51$), suggesting deteriorating oxygen conditions in the lake during the open-water period as regional climate warming continues. The greatest oxygen depletion in the lake occurs in winters with early freeze-up and late ice-breaking. The inverse correlation of the duration of winter hypoxia with the November air temperature of the previous year ($R^2 = 0.39$) and the May air temperature of the current year ($R^2 = 0.41$), which influence the timing of ice formation and breakup, suggests the oxygen conditions in the lake during the winter have improved, with a shorter freeze-up period due to warming in the fall and spring. The observed changes in the water chemical composition provide reasoning for reducing the trout farming volumes.

KEYWORDS: small lake, human impact, climate change, major ions, nutrients, oxygen

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INTRODUCTION

Lakes are vulnerable to anthropogenic impacts and climate change (Adrian et al. 2009; Maberly et al. 2020; Saros et al. 2023; Woolway et al. 2025). Shifts in water temperature (O'Reilly et al. 2015), ice phenology (Sharma et al. 2019), oxygen content (Jansen et al. 2024), mixing patterns (Woolway and Merchant 2019), and biogeochemical cycles (Hobbie et al. 1999; Bush et al. 2017; Joung et al. 2017; Quinlan et al. 2021; Wu et al. 2022; Zhu et al. 2025) have been detected in lakes around the world

in response to global warming and growing nutrient loading. In small lakes, due to their small volume, changes occur very quickly (Wik et al. 2016; Wu et al. 2022), which raises the relevance of studying changes in the chemical composition of such lakes under the influence of climate change and human impact.

There are more than 60 thousand lakes in Karelia, most of which are small (Lakes... 2013). In recent decades, Karelia has experienced a steady increase in air temperature (the rate of increase in average annual air temperature was +0.5–0.6 °C/

decade (Nazarova et al. 2022) in 1976–2021) and a change in precipitation (20–70 mm surplus in annual precipitation relative to the 1961–1990 baseline (Nazarova 2015)). Coupled with intensive economic use of the catchments, this contributes to changes in the input of organic matter (OM) and nutrients to lakes (Sabylina et al. 2010). The impact of trout farms on lake ecosystems (Galakhina and Zobkov 2022) is the most acute problem for Karelia, since fish production volumes are constantly growing.

Lake Vendyurskoe is a small lake in southern Karelia, located 50–100 km away from large industrial areas but affected by fish farming since 2009. There are no farmlands in the Lake Vendyurskoe catchment. Logging and drainage between 1971 and 1986 have significantly altered the landscape in the catchment. Drainage caused lake water enrichment with OM, inorganic substances, and nutrients, but the operations ceased after 1991.

Previously, the chemical composition of the lake water was studied in the summers of 1971, 1972, 1978, 1983, 1986, 1991, 1992 and seasonally in 1979–1990 (excluding 1982, 1983, 1986). Lake Vendyurskoe was a model for studying the acidifying effect of polluted precipitation in 1981–1986 (Kharkevich and Kryukova 1981; Freindling and Kharkevich 1982; Martynova 1982). After 1992, the sampling frequency was sharply reduced for a number of reasons (lack of funding, change in the Institute's research topics), and hydrochemical studies were carried out at intervals of 9–10 years in 2001, 2011/2012 and 2021–2023. The chemical composition of water in tributaries to Lake Vendyurskoe was studied in 1976–1985 and 2001.

The purpose of this study is to assess changes in the chemical composition of Lake Vendyurskoe water over 50 years, which occurred as a result of the economic activities in its catchment area, fish farming inside the lake, and regional climate variability.

MATERIALS AND METHODS

Lake Vendyurskoe is located in southern Karelia (62°10′–62°20′ N, 33°10′–33°20′ E) and belongs to the basin of the Suna River, a tributary of Lake Onega (Fig. 1a, b). The lake is of glacial origin, with an area of 10.1 km² and water volume of 0.0609 km³ (Lakes... 2013). The catchment is ~15% paludal. The Rindozherka River and several streams empty into the lake, while the Kulapdegi River originates from it. The total average annual runoff into the lake (according to V.A. Freindling and N.S. Kharkevich, archival records of the Northern Water Problems Institute) is 22.2×10⁶ m³, with the Rindozherka River accounting for about 43%. Atmospheric precipitation over the lake surface is 6.5×10⁶ m³ (Lakes... 2013). The lake is ice-covered for 5–6 months, from November or the first half of December to late April–early May. In the summer, the surface water layers warm up to 20–25°C and the bottom layers to 15–17°C. During the open water period, the lake becomes completely mixed 3–7 times (Smirnov et al. 2024), and so it classifies as polymictic.

Water sampling in Lake Vendyurskoe was carried out in the summers of 1971, 1972, 1978 and seasonally in 1979–1980, 1983–1985, 1987, 1990–1992, 2001, 2011–2012, 2021–2023 at the same stations (Fig. 1c).

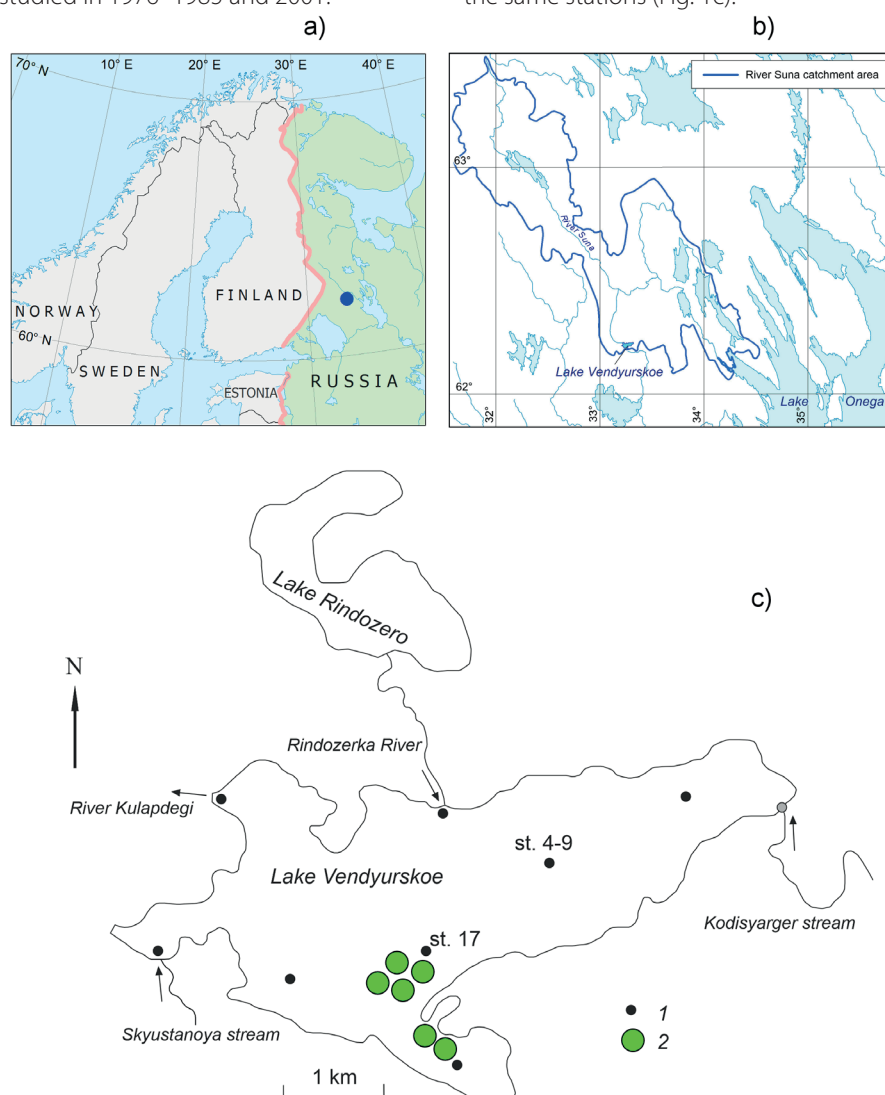


Fig. 1. (a) Location of Lake Vendyurskoe (blue circle). (b) Lake Vendyurskoe in the Suna River catchment area. (c) Measurement stations (1) and trout cages (2)

Water sampling in tributaries to Lake Vendyurskoe was carried out in 1976–1985 and 2021–2023 on Kodisyarger and Skyustanoya Brooks and in 1971–1991, 2001, and 2021–2023 on the Rindozerka River. Water samples were collected by Niskin bottles from the surface and bottom layers. The samples for total phosphorus and iron (250 mL) were acidified with H_2SO_4 solution immediately after sampling. Water from the lake and its tributaries was tested for total dissolved solids (TDS) and concentrations of major ions and nutrients (nitrogen, phosphorus, iron, silicon). Also, pH, OM proxies (color, permanganate (COD_{Mn}) and bichromate (COD_{Cr}) chemical oxygen demand, five-day biological oxygen demand BOD_5 , ratio of COD_{Mn} to COD_{Cr}), and concentrations of oxygen and carbon dioxide were determined in the lake water. Chemical analyses were performed in the Laboratory of Hydrochemistry and Hydrogeology of the Northern Water Problems Institute using equipment of the Core Facility of the Karelian Research Centre RAS. Standard laboratory analysis methods were used throughout the study period (Lozovik 1994; Analytical... 2017). It should be noted that iron (Fe_{tot}) determination methods varied during the 50-year period. In the 1970s, iron determination was performed with ammonium rhodanide; in the 1980s – with ortho-phenanthroline; and lately – by atomic absorption spectrometry. The results obtained by the last two methods showed good convergence (Lozovik et al. 2006).

The exogenous load of total phosphorus (Lp) on the lake is calculated from the weighted average concentration of total phosphorus (Ppr) using the Eq. (1) (Gusakov 1987):

$$[Ppr] = \frac{Lp}{\bar{z}S} \quad (1)$$

where $\bar{z}$ is the average depth, m; S is the residence time, year⁻¹; the values for Lake Vendyurskoe are $\bar{z} = 5.3$ m and $S = 0.44$ year⁻¹.

To identify changes in the chemical composition of water in Lake Vendyurskoe and its tributaries over a long time period, we employed the following approach. Taking into account the heterogeneity of the data series (changes in the sampling frequency, large gaps in the data series), it was decided to compare two base periods that corresponded to the “past” (1971–1992 for the lake and 1979–1985 for the tributaries) and “current” (2021–2023 both for the lake and the tributaries) conditions.

Sofa Statistics 1.4.6 software was used for statistical data processing. The chemical analysis data (P_{tot} , P_{min}) followed a normal distribution. The number of samples analyzed was $n = 28$ (1971–2001 and 2021–2023). Spearman's test was used to determine statistically significant differences in the content of P_{tot} and P_{min} between the survey periods. The paired t-test was used to identify statistically significant differences in the studied components (COD_{Cr} , COD_{Mn} , pH, BOD_5 , HCO_3^- , Cl^- , SO_4^{2-} , CO_2) in different periods (1971–1990 and 2021–2023).

Additional valuable information about the oxygen regime of the lake was obtained by analyzing records from an autonomous measurement station – a chain with temperature and dissolved oxygen (DO) sensors (RBR Ltd., Canada), which was deployed in the central deep-water part of Lake Vendyurskoe (St. 4–9, see Fig. 1b) in July 2007 and has been operating year-round since then. This article summarizes the data from 2007 to 2023. Records were collected from 10–15 temperature sensors (0.002 °C accuracy) and 4–5 DO sensors (0–150% oxygen range, 1% accuracy) distributed evenly throughout the water column, taking measurements at one-minute intervals. The oxygen sensor located at 0.5–0.7 m above the bottom was used to

determine hypoxia periods (DO below 2 mg/L).

Data on the weather conditions were taken from the Petrozavodsk Weather Station (Bulygina et al. 2025). The air temperature and precipitation were analyzed for each year, and the precipitation volumes were calculated per decade (1970–1979, 1980–1989, etc.). The average precipitation amounts from November of the previous year to July of the current year were calculated to determine the effect of lake water volume fluctuations across years on the concentration of bicarbonates in the lake water. The relationship between the duration of hypoxia (< 2 mg/L) at the bottom of the central basin of the lake and the average air temperature of the three summer months was analyzed. For the winter period, we analyzed the relationships between hypoxia duration and air temperatures in November and May as factors that can determine the ice-on and ice-off dates and, consequently, the duration of the winter hypoxia.

RESULTS and discussion

Chemical composition of water in the lake's tributaries

Over the long-term period, the annual average TDS in the Rindozerka River and the brooks decreased, presumably due to regional climate change and alteration of the landscape structure in the catchment area (deforestation and drainage). According to seasonal data for 1979–1985 and for 2021–2023, the annual average TDS in the Rindozerka River, Kodisyarger, and Skyustanoya Brooks was 19.4, 24.2, and 30.2 mg/L, and 13.7, 16.4, and 20.3 mg/L, respectively.

From 1975 to 1983, hydrological engineering was implemented in the northern and northeastern parts of Lake Vendyurskoe catchment (79.8 km²) to reclaim wetlands, which covered ~15% of the area. Forest drainage was the most intensive in the catchment of Lake Rindozero (32.9 km²), which is within Lake Vendyurskoe catchment. The proportion of drained land in its northern and northeastern parts amounted to 20% of Lake Vendyurskoe catchment area. Monthly hydrochemical observations were carried out from October 1978 to June 1981 in two main canals draining fens and transitional mires with peat deposits up to 2 m thick (Kharkevich et al. 1982). The TDS content of water in the drains was closely correlated with the water regime: the average values during low-water periods were 47.5 mg/L (in summer) and 66.3 mg/L (in winter). The water was of the calcium-rich hydrocarbonate type. Sulfate ion concentrations in summer and winter were 4.6 and 5.9 mg/L, respectively. During the high-water period, TDS decreased to 24.3 mg/L, the value during freshets being 36.5 mg/L. During this time, the water class changed from the bicarbonate to the sulfate type. The sulfate content during the flood period rose to 12.9–13.9 mg/L (8.6 on average). The average concentration of inorganic phosphorus (P_{min}) in the canal water was at maximum (42 µg/L) in 1979 and decreased to 10–15 µg/L by 1981. In the summer of 1979, there was also an elevated content of ammonium nitrogen, up to 0.81 mg/L (average annual 0.28 mg/L). In 1981, the average annual content of ammonium nitrogen dropped to 0.20 mg/L. The average annual concentration of nitrate nitrogen was an order of magnitude lower.

Drainage-induced ecosystem transformation in the taiga zone of northern European Russia is most intensive during the first 3–4 years and ends after 10 years. The anthropogenic load of total nitrogen and phosphorus from forestry areas in the catchments of southern Karelia in the first years after drainage accounts for 11% and 10% of river flow, respectively (Karpechko 2004). In subsequent years,

the effect of forest drainage on the flow of chemicals from drained land to the stream is insignificant. After that, the formation of the hydrological and chemical runoff in the drained wetlands is the same as in the rest of the forest area.

The current reduction in water mineralization in the tributaries is primarily due to a decrease in the concentrations of sulfate and chloride ions. In 1979–1985, the average annual content of sulfate and chloride ions was 4.6 and 1.2 mg/L, respectively. In 2021–2023, the concentration of sulfate ions dropped 4.5-fold and that of chloride ions 1.7-fold. In the past, the increased content of sulfate and chloride ions in the lake was due to the influx of water from drained lands and precipitation. In the early 1990s, ameliorative operations in Lake Rindozero catchment were terminated. The average annual concentration of sulfate ions in atmospheric precipitation in Lake Vendyurskoe catchment in 1981–1984 was 2.1 mg/L (Kharkevich and Kryukova 1981; Kharkevich et al. 1982; Sabylina and Basov 2003) and in 2021–2023 it was 0.9 mg/L.

Nutrients in the water of the tributaries have exhibited little change. For example, the average annual concentration of total phosphorus in the water of the Rindozerk River and the Kodisyarger Brook in the early 1980s was 22 and 39 µg/L, respectively, while by 2021–2023 it had increased 1.3-fold. The weighted average concentration of total phosphorus in the lake's tributaries in 2021–2023 was 30 µg/L; the exogenous load of total phosphorus (L_p) on the lake was 0.07 g/(m²·year). These levels correspond to oligotrophic conditions (Dillon and Rigler 1974).

The average annual concentration of ammonium and nitrate nitrogen in the water of the Rindozerk River in the past (0.04 mg/L) was close to the current level (0.05 mg/L). Within-year fluctuations also remained the same: ammonium nitrogen is the highest in the spring (0.11 mg/L) and nitrate in the winter (0.08 mg/L). Organic nitrogen (0.35 mg/L) contributes 54% to the total nitrogen. The average annual concentration of total nitrogen in the tributaries is 0.67 mg/L. The current exogenous load of total nitrogen is low and amounts to 1.6 g/(m²·year), which corresponds to an oligotrophic state.

The average annual silicon content in the Rindozerk River during earlier studies was 2.9 mg/L, and the current content is close to that level – 2.6 mg/L.

The total iron concentration in the water of the Rindozerk River and the Kodisyarger Brook has changed little over time, being 0.80 and 3.0 mg/L, respectively.

OM proxy indicators in the tributary water varied widely in 2021–2023: color from 28 to 194 degrees, and COD_{Mn} from 7.1 to 23.4 mgO/L. The values were the lowest for the Rindozerk River.

The water pH in the tributaries is low (6.33–6.85), with little variation over time.

Chemical composition of Lake Vendyurskoe water

The chemical composition of water in Lake Vendyurskoe is mainly shaped by the river runoff – Rindozerk River,

Kodisyarger, and Skyustanoya Brooks, as well as by precipitation, baseflow, and anthropogenic impact.

Due to the natural characteristics of the catchment area, especially the fluvio-glacial genesis and edaphic conditions, the content of total dissolved solids in Lake Vendyurskoe water is low (TDS < 50 mg/L). The average annual TDS currently is 15.7 mg/L, while in 1971–1992 it was up to 21.1 mg/L (Table 1). Studies show (Tables 1 and 2) that there have been no noticeable changes in the cationic composition of the water. In the anionic composition, the content of bicarbonates, sulfate and chloride ions has changed over the 50 years. The concentration of chloride ions has dropped by half from the 1970s to the present (Table 1). A statistically significant difference in chloride content ($p < 0.001$ ($1.852 \cdot 10^{-6}$)) and bicarbonates ($p < 0.001$ ($3.656 \cdot 10^{-5}$)) was confirmed for the two study periods (1971–1992 and 2021–2023) using a paired t-test. In the summer seasons of 1971–1984, the proportion of sulfates in the anion composition remained quite constant (4.86 mg/L on average) (Table 3), but starting from 1985, their concentration has been declining, with a 4-fold reduction by 2021–2023 (paired t-test; $p < 0.001$ ($3.265 \cdot 10^{-20}$)) (see Tables 1 and 3, Fig. 2a). The decrease in the concentration of sulfates in lake water is a consequence of their reduction in atmospheric precipitation due to a decrease in economic activity in the region and in the catchment area (Lozovik and Potapova 2006). Lake acidification was observed throughout Northern Europe and North America in the mid-20th century, resulting from the precipitation of sulfates from atmospheric emissions. However, regulatory measures adopted in the 1980s (Grennfelt et al. 2020) led to a general decline in sulfate concentrations in lakes. A large-scale study of changes in the chemical composition of Finnish (Forsius et al. 2003) and Canadian (Mazoyer and Houle 2025) lakes found that sulfate concentrations decreased in recent decades, indicating a clear response to reduced sulfate emissions.

The proportion of hydrocarbonates in the anion composition throughout the research period varied from 8.3 to 15.2 mg/L (Table 3, Fig. 2). Based on the available measurement data for different years, an inverse correlation was found between the hydrocarbonate concentration and the precipitation amount from November of the previous year to July of the current year (Fig. 2b), with the determination coefficient $R^2 = 0.36$ (excluding the data for 1983 with the maximum HCO_3^- value). It is unclear what caused the extremely high hydrocarbonate concentration in the summer of 1983 (15.2 mg/L), given the rather high precipitation amount from November to July (428 mm). A significant increase in precipitation (by 65–80 mm between November to July over the past 50 years (Fig. 2a)) may be one of the reasons for the decrease in the lake's HCO_3^- in summer at present versus 1971–1987.

During the low-water periods of 2021–2023, TDS in the lake exhibited minor vertical heterogeneity. The maximum was observed at the bottom in late March and early August, with an increased role of groundwater recharge (the TDS gradient between the surface and bottom layers during these periods was 2–3 mg/L) (see Table 2).

Table 1. Average annual content of total dissolved solids (TDS) (mg/L) and concentrations of major ions (mg/L) in Lake Vendyurskoe water in 1971–1990 and 2021–2023

Years	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	HCO ₃ ⁻	SO ₄ ²⁻	Cl ⁻	TDS
1971–1990	2.3	0.9	0.5	1.3	11.6	3.2	1.3	21.1
2021–2023	1.9	0.7	0.6	1.5	9.1	1.0	0.7	15.6

Table 2. Total dissolved solids (TDS) and concentrations of major ions in the surface and bottom layers of Lake Vendyurskoe water in 2021–2023 (above the line – mg/L, below the line – %eq.)

Season	Layer	Ca ²⁺	Mg ²⁺	K ⁺	Na ⁺	HCO ₃ ⁻	SO ₄ ²⁻	Cl ⁻	TDS
Winter	surface	1.8/41.7	0.6/22.8	0.6/7.2	1.4/28.3	8.5/78.4	0.9/10.5	0.7/11.1	14.5
	near-bottom	1.8/41.7	0.6/22.8	0.6/7.2	1.4/28.3	8.5/74.9	1.3/14.6	0.7/10.6	14.9
Spring	surface	1.8/38.7	0.7/24.7	0.6/6.6	1.6/30.0	9.5/80.2	0.9/9.6	0.7/10.1	15.8
	near-bottom	1.9/39.3	0.7/23.8	0.6/6.4	1.7/30.6	10.3/80.3	0.9/8.9	0.8/10.8	16.9
Summer	surface	2.0/42.6	0.6/21.0	0.6/6.6	1.6/29.7	8.8/76.0	1.1/12.1	0.8/11.9	15.5
	near-bottom	2.0/43.5	0.6/21.4	0.6/6.7	1.5/28.4	9.3/79.0	1.0/10.8	0.7/10.2	15.7
Autumn	surface	1.9/39.5	0.7/23.9	0.7/7.5	1.6/29.0	8.3/78.0	0.9/10.7	0.7/11.3	14.9
	near-bottom	2.2/43.5	0.7/22.8	0.6/6.1	1.6/27.6	9.6/78.4	1.0/10.4	0.8/11.3	16.4

Table 3. Average hydrocarbonate and sulfate ion levels in Lake Vendyurskoe in summer in different years

Year	HCO ₃ ⁻ , mg/L	SO ₄ ²⁻ , mg/L
1971	9.8	4.7
1972	13.3	4.0
1978	9.8	4.7
1979	13.6	4.7
1980	9.1	4.2
1983	15.2	4.9
1984	11.0	4.5
1985	12.8	3.2
1987	10.8	3.4
1990	9.6	2.7
1991	10.3	2.6
2001	10.1	2.3
2011	9.3	1.3
2012	9.0	1.5
2021	9.7	1.3
2022	8.9	1.2
2023	8.3	1.3

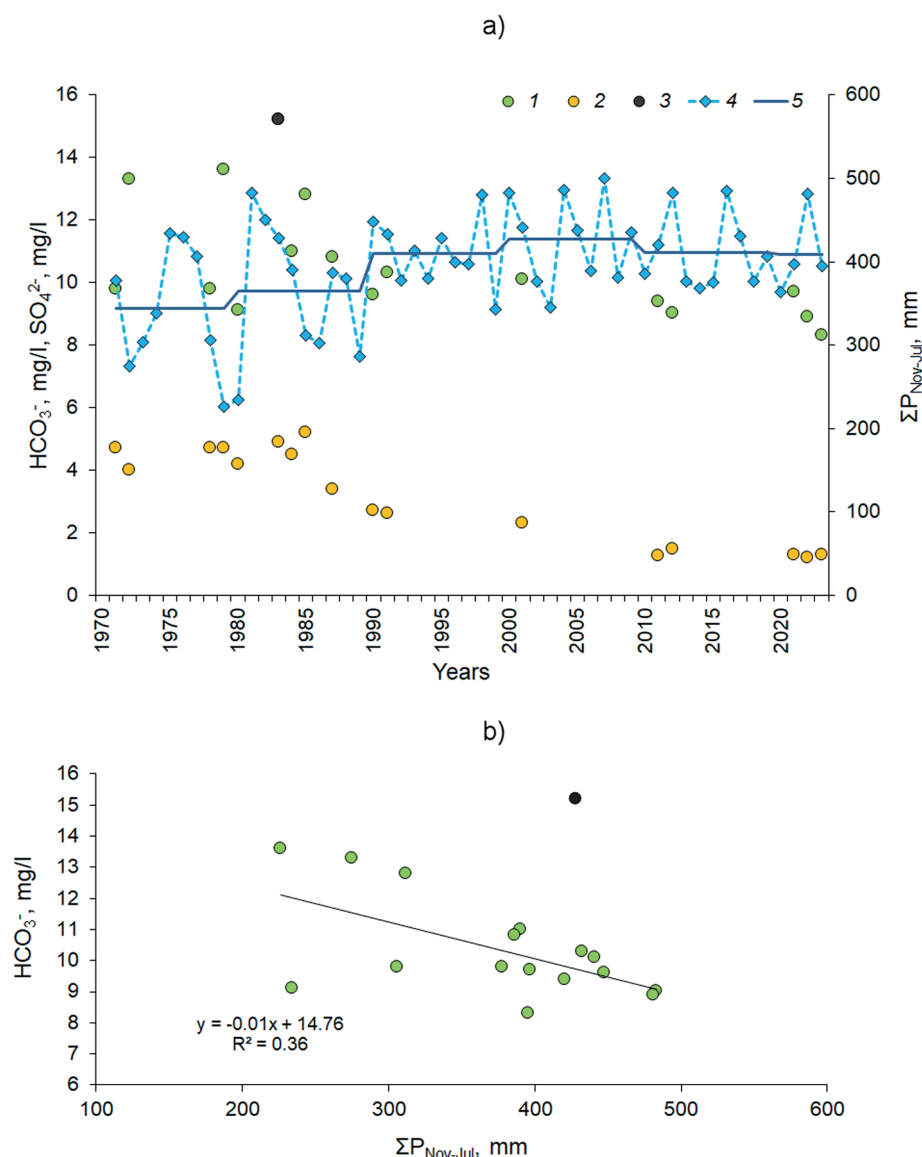


Fig. 2. (a) Concentrations of HCO_3^- (1) and SO_4^{2-} (2) in Lake Vendyurskoe water in summer in different years; HCO_3^- in the summer of 1983 (3); $\Sigma\text{P}_{\text{Nov-Jul}}$ – total precipitation from November of the previous year to July of the current year (4); $\Sigma\text{P}_{\text{Nov-Jul}}$ averaged per decade (5). (b) Relationship between HCO_3^- and $\Sigma\text{P}_{\text{Nov-Jul}}$

Thus, according to the classification of Alekin (1970), water in Lake Vendyurskoe belongs to the calcium group of the hydrocarbonate class.

In 2021–2023, pH fluctuated slightly within a year: the minimum in winter was 6.20–6.40, the maximum in summer was 6.60–7.03 (surface layer), and the annual average was 6.64. The pH gradient in the water column was also small: pH in the bottom water layers was lower than in the surface layers by only 0.3–0.7 units. In 1971–1992, pH varied from 6.0 to 7.4 (6.76 on average). Thus, no significant decrease in pH was observed between the two study periods ($p > 0.001$ (0.015)).

Organic matter (OM). Large-scale studies of OM dynamics in the lake in 1971–1992 showed that the water color varied from 15 to 55 mg Pt-Co/L (40 mg Pt-Co/L on average), COD_{Mn} – from 4.6 to 8.9 mgO/L (7.4 mgO/L on average), and COD_{Cr} – from 9.3 to 20.5 mgO/L (16.8 mgO/L on average) (Table 4). Fluctuations of these indicators across the lake area and between the upper and bottom water layers were insignificant, with a slight rise in the area influenced by humus-rich water of the Rindozherka River (Freindling and Kharkevich 1982; Sabylina and Basov 2003).

A statistically significant difference in the content of COD_{Mn} (paired t-test; $p < 0.001$ ($1.383 \cdot 10^{-3}$)) and COD_{Cr} (paired t-test; $p < 0.001$ ($2.125 \cdot 10^{-8}$)) for the two study

periods was confirmed. According to the test, the content of OM (COD_{Cr} and COD_{Mn}) is now 1.2 times higher. For BOD_5 , no statistically significant difference between the two study periods was detected ($p > 0.001$ (0.6778)).

During both study periods, BOD_5 values in the lake were the highest in the autumn and the lowest in the winter (Table 4). As reported by Slastina et al. (2022), the bulk of the lake's phytoplankton biomass in the autumn is formed by diatoms, both in the central part of the lake (83–99%) and near the trout farm (96–99%). The contribution of other algal groups is insignificant. The concentration of labile OM in the summer, characterized by the ratio of BOD_5 to COD_{Cr} , has been the same in the past and in the current period (6–7%), but with a rise to 12% around trout cages.

The main driver of bioproductivity in Lake Vendyurskoe is trout farming, as there are no other significant sources of nutrients: there is no farmland in the catchment area, and the village on the shore has only a few houses and is populated only in the summer. Meanwhile, studies conducted on other lakes with operating trout farms in Karelia prove the facilities release nutrients into water (Mikhailenko and Sterligova 2021; Galakhina and Zobkov 2022).

Table 4. Average content of OM proxies in the water of Lake Vendyurskoe in 1971–1992 (I) and 2021–2023 (II)

Period	Season	Layer	Color mg Pt-Co/L	COD _{Mn} , mgO/L	COD _{Cr} , mgO/L	BOD ₅ , mgO ₂ /L	COD _{Mn} /COD _{Cr} , %
I	Winter	surface	46	8.0	18.2	1.2	44
		near-bottom	51	7.8	17.0	1.3	46
	Spring	surface	50	8.4	17.7	1.5	47
		near-bottom	51	7.8	17.1	1.2	46
	Summer	surface	33	7.4	16.9	1.2	44
		near-bottom	34	6.7	16.6	1.1	40
	Autumn	surface	28	6.6	15.6	1.3	42
		near-bottom	27	6.8	15.8	1.3	43
II	Winter	surface	35	6.8	16.8	0.8	39
		near-bottom	46	8.0	18.4	0.6	43
	Spring	surface	49	8.1	21.6	1.1	37
		near-bottom	50	7.5	20.5	0.8	36
	Summer	surface	27	8.0	24.8	1.5	37
		near-bottom	39	6.9	20.9	1.2	33
	Autumn	surface	30	8.2	22.1	1.6	37
		near-bottom	31	6.9	19.0	1.4	36

Gas conditions and the hydrogen index. In 1971–1992, the oxygen concentration in the surface layers of Lake Vendyurskoe varied within the range of 6.7–12.0 mg/L. Currently, it remains close to this level, at 6.9–11.8 mg/L.

Data for 2007–2023 from the autonomous measurement station indicate that the bottom layers of the central, deep-water basin developed hypoxia (oxygen concentration below 2 mg/L) every winter and summer, with increased stratification. During the open-water period, hypoxia duration varies across years from 1–2 weeks to 46 days (18 days on average). A direct correlation was found between the average air temperature of the three summer months and the duration of oxygen deficiency (2007–2023), with the determination coefficient $R^2 = 0.51$ (Fig. 3a). Hypoxia lasted the longest in the warm summer seasons of 2010, 2013, 2016, 2021, and 2022, when the average air temperature of the three summer months was 16–17 °C (with a baseline of 14.5 °C), stratification of the water column was more pronounced and persisted longer (Smirnov et al. 2024). In the cooler summers of 2007, 2012, 2015, 2017, 2019, and 2020, with an average air temperature of the three summer months close to or slightly above the baseline (14.4–15.6 °C), the water column of the lake was periodically mixed, the bottom layers were aerated, and hypoxia time was shorter. The duration of hypoxia in winter was 47–167 days in different years (96 on average). The poorest oxygen conditions were observed in the winters of 2007/08, 2016/17, 2021/22, which were characterized by a cold pre-freeze period (November temperature –3–4 °C, i.e. 0.5–1.5 °C below the baseline) and early ice-on and a cool spring period (May temperature +5+7 °C, i.e. 1.5–3.5 °C below the baseline) with late ice-off. An inverse correlation

was found between the duration of hypoxia in winter and the air temperature in November of the previous year and May of the current year, with the determination coefficients $R^2 = 0.39$ (Fig. 3b) and $R^2 = 0.41$ (Fig. 3c). The series of observations at the autonomous station is too short (15 years) to identify a statistically significant trend in the duration of bottom hypoxia. However, judging by the revealed correlations, the ongoing regional warming (increase in air temperature in the summer months) will negatively affect the oxygen conditions in the lake in summer. At the same time, an increase in air temperature in autumn and spring will result in a later ice-on and an earlier ice-melt, so the period of bottom-layer hypoxia in winter will be reduced.

The spring overturn occurs at low water temperatures (4–10°C). The oxygen saturation of the water mass is fairly uniform – 89% on average. By the time the summer stratification is established, the lake has a good supply of oxygen. The oxygen content in the surface layers of water in summer does not exceed 90–95%, which indicates a low activity of phytoplanktic photosynthesis. The oxygen content in the bottom layer of the lake's deep-water parts does not exceed 10–20%, and the concentration of carbon dioxide increases to 4.9–5.3 mg/L versus 2.2–2.8 mg/L in the surface layer. The water pH values decrease from 6.94–7.01 in the surface layers to 6.69–6.89 in the bottom layers of water. The oxygen conditions around trout cages (the southern part of the lake) at the beginning of the summer of 2022 were the following: the oxygen content was 8.8 mg/L (84% saturation) in the surface layer and 5.4 mg/L (48% saturation) in the bottom layer. During the autumn overturn, the deep water layers are involved in the

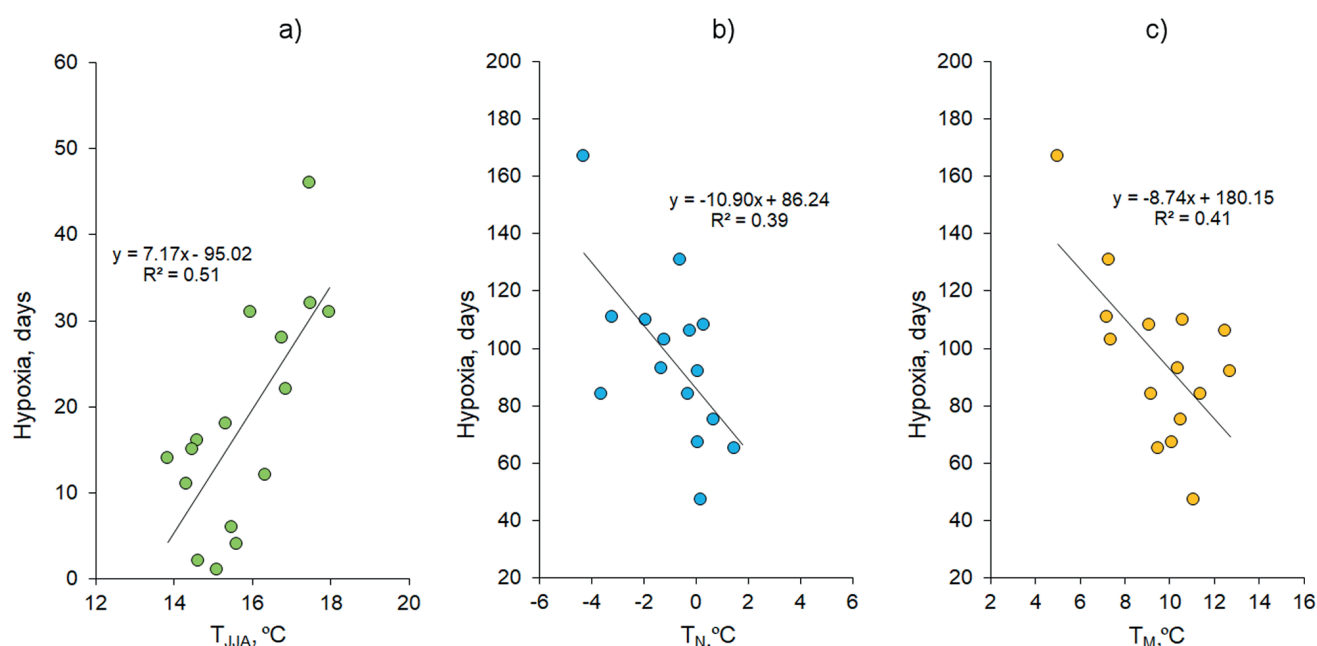


Fig. 3. Duration of hypoxia in Lake Vendyurskoe in 2007–2023 in summer (a) and winter (b, c) depending on the average air temperature in the summer months (a), in November of the previous year (b), and in May of the current year (c)

convection, and the entire water column is enriched with oxygen. Its average concentration in the lake is 10.5 mg/L.

The content of carbon dioxide in the surface and bottom layers of water in Lake Vendyurskoe varied in 2021–2023 from 2.1 to 2.9 and from 1.8 to 6.9 mg/L, respectively. The highest concentrations of CO_2 were noted in winter and the lowest – in spring and autumn. No statistically significant difference in the content of CO_2 in the two study periods (1971–1992 and 2021–2023) was detected (paired t-test; $p > 0.001$ (0.7603)). The mean CO_2 value in the past was 4.27, while at present it is 4.06 mg/L. Thus, the carbon dioxide content in the lake water has not changed significantly over the 50-year period.

Nutrients. To assess the current trophic status of the lake and to identify long-term trends, it is important to have information about the content and patterns of nutrients, first of all phosphorus. In Lake Vendyurskoe, measurements of inorganic (P_{min}) and total phosphorus (P_{tot}) began in 1971. The P_{min} concentration in 1971–1991 and 2001 varied from 3 to 8 $\mu\text{g/L}$, with an annual average of 3 $\mu\text{g/L}$. Season-wise, their concentrations were the highest in winter. In summer, the concentration of P_{min} did not exceed 3 $\mu\text{g/L}$, with the highest concentrations in October and November – 5–8 $\mu\text{g/L}$. The P_{tot} content varied within 13–25 $\mu\text{g/L}$ (18 $\mu\text{g/L}$ on average). The seasonal variation of P_{tot} concentrations was similar to that of P_{min} (Freindling and Kharkevich 1982; Sabylina and Basov 2003). The influx of inorganic and total phosphorus into Lake Vendyurskoe from the catchment area exhibited a minor change over the study period. At the same time, the direct input increased due to trout farming.

The wintertime concentration of P_{min} in the near-bottom water layers averaged 7–8 $\mu\text{g/L}$ in the earlier years, while in 2021–2023 it increased to 11 $\mu\text{g/L}$ in the central, deep-water part of the lake and to 17 $\mu\text{g/L}$ near the trout cages (Tables 5, 6).

At the current stage, vertical differentiation of P_{min} has become clearly expressed in the deep-water area (st. 4–9) during the summer stratification. The difference between its concentration in the surface and near-bottom layers of water is up to 9 $\mu\text{g/L}$. In summer, the consumption of P_{min} by phytoplankton in the surface layers leads to below-detection levels throughout the lake.

The concentration of phosphates during the summer stratification averages 8 $\mu\text{g/L}$ in the hypolimnion of the deep-

water region of the lake (at 5 and 10 m depths) and near trout cages (5 m). This is due to the fact that the environmental conditions (pH, Eh) now forming in the hypolimnion induce a mobilization of P-PO_4 from bottom sediments into the water. Let us consider this process through the case study of a station located in the pelagic area of the lake and near the trout farm (Table 7). The water in the lake is enriched with humic substances (water color 40–56 mg Pt-Co/L, COD_{Mn} – 7–8 mgO/L) and total iron (summer concentration 0.34–0.45 mg/L), and is very soft (average water hardness is 0.41 mg-mol/L). Due to this, P-PO_4 is mobilized from bottom sediments into the water. Sorption of P-PO_4 on humates occurs by their binding with iron. Oxygen depletion in the bottom layers of water (to 48–52%) triggers reduction processes (Table 7). The concentration of ammonium ions in the near-bottom layers is 2 times higher than in the surface layers. Ammonification processes prevail at the bottom. Ammonium concentration rises to 49–114 $\mu\text{g/L}$. As Fe^{3+} is reduced to Fe^{2+} , the sorbed P-PO_4 is released into the water. The concentration of phosphates in the bottom layers increases to 9–36 $\mu\text{g/L}$. The content of ferrous iron increases by 1.5 times. The processes of phosphorus mobilization under reducing conditions in oxygen-depleted near-bottom water have been described for a number of lakes (Nürnberg et al. 2013; Joung et al. 2017).

Thus, during the summer stratification, phosphorus in the deep-water area of the lake and near the trout cages is mobilized from sediments, creating additional (endogenous) phosphorus load. This could stimulate further growth of phytoplankton in the lake, regardless of the amount of phosphorus coming from the catchment area, and contribute to the transition of the lake to a mesotrophic state. In autumn, due to active mixing and a decrease in phosphate consumption by algae, the phosphate concentration is equalized across the water area and depth (see Tables 5, 6). In 2021–2023, P_{tot} concentration in the lake varied from 11 to 68 $\mu\text{g/L}$. Its average annual concentration was 23 $\mu\text{g/L}$. Average annual P_{min} was 16% of the total, and its share in winter was 50–90%.

Total phosphorus content showed an upward trend over the 50-year period in both the surface ($p = 2.665 \cdot 10^{-4}$, $R = 0.65$) and near-bottom ($p = 1.367 \cdot 10^{-5}$, $R = 0.73$) layers (Spearman test; $p < 0.05$; number of samples (n) = 28). The increase in P_{min} content in the near-bottom layer has been

Table 5. Average content of nutrients in the water of Lake Vendyurskoe (excluding the station near the trout farm) in 2021–2023

Season	Layer	N, mg/L				P, µg/L		Fe _{tot} , mg/L	Si, mg/L
		NH ₄ ⁺	NO ₃ ⁻	N _{org}	TN	P _{min}	P _{tot}		
Winter	surface	0.05	0.05	0.28	0.38	5	13	0.18	0.8
	near-bottom	0.05	0.11	0.23	0.39	11	16	0.37	1.5
Spring	surface	0.06	0.04	0.22	0.32	3	19	0.42	1.6
	near-bottom	0.10	0.04	0.27	0.41	4	19	0.47	1.6
Summer	surface	0.06	<0.01	0.51	0.58	1	28	0.34	1.8
	near-bottom	0.10	<0.01	0.46	0.57	4	30	0.49	1.9
Autumn	surface	0.06	<0.01	0.32	0.39	4	25	0.25	0.1
	near-bottom	0.06	<0.01	0.26	0.32	4	26	0.30	0.1

Table 6. Nutrients around trout cages (St. 17) in Lake Vendyurskoe in 2021–2023

Season	Layer	N, mg/L				P, µg/L		Fe _{tot} , mg/L	Si, mg/L
		NH ₄ ⁺	NO ₃ ⁻	N _{org}	TN	P _{min}	P _{tot}		
Winter	surface	0.04	0.06	0.28	0.38	7	17	0.18	0.8
	near-bottom	0.02	0.10	0.30	0.42	17	28	0.35	1.3
Spring	surface	0.11	0.03	0.27	0.41	4	22	0.42	1.6
	near-bottom	0.09	0.04	0.27	0.39	3	24	0.43	1.6
Summer	surface	0.09	<0.01	0.35	0.44	1	25	0.34	1.8
	near-bottom	0.03	<0.01	0.36	0.39	8	47	0.52	1.7
Autumn	surface	0.07	<0.01	0.37	0.44		31	0.24	0.1
	near-bottom	0.09	0.01	0.28	0.37	4	27	0.26	0.1

Table 7. The content of some components of the chemical composition of water in Lake Vendyurskoe at the early summer (June 22, 2022)

Station	Depth, m	pH	Eh, mV	(O ₂ , mg/l)/(%)	P _{min} , µg/L	NH ₄ -N, µg/L	Fe, mg/L	
							Fe ²⁺	Fe ³⁺
St. 4-9	0.5	7.01	220	8.9/88	1	54	0.028	0.35
	11.0	6.45	215	5.6/52	9	61	0.034	0.55
St. 17	0.5	7.10	235	8.8/84	2	49	0.032	0.34
	8.0	6.42	225	5.4/48	36	114	0.048	0.71

minor ($p < 0.05$, $R = 0.327$), and no statistically significant difference was found in the surface layer over a long-term period.

The second component affecting primary productivity is nitrogen. Nitrate nitrogen enters the lake with river runoff, atmospheric precipitation, and as a result of bacterial transformation of nitrogen compounds during the destruction and mineralization of autochthonous and allochthonous OM.

The concentration of $\text{NO}_3\text{-N}$ in 1971–1992 and 2001 varied from < 0.01 to 0.17 mg/L, with an average annual value of 0.10 mg/L. Maximum concentrations of $0.05\text{--}0.17$ mg/L were observed in winter, when nitrification processes prevail, and minimum – in the spring-summer period of phytoplankton development: $< 0.01\text{--}0.09$ mg/L in spring (0.05 mg/L on average) and $< 0.01\text{--}0.05$ mg/L in summer (0.02 mg/L on average).

The concentration of $\text{NO}_3\text{-N}$ in 2021–2023 varied from < 0.01 to 0.19 mg/L. Its assimilation by phytoplankton now increased in the summer-autumn period, while previously it tended to rise in the spring-summer period. In winter, the $\text{NO}_3\text{-N}$ concentration reached its highest values of the year – up to 0.19 mg/L, with an average of 0.11 mg/L, because during this time of the year, nitrification processes prevail throughout the water column. The exception is the bottom layers of water near trout cages, where in the winter of 2021 low concentrations of nitrates (0.02 mg/L), elevated concentrations of nitrites (< 0.01 mg/L), hypoxia (40%) and an increase in phosphate concentrations to 17 $\mu\text{g/L}$ were observed.

In spring, nitrate ions begin to be actively assimilated by growing phytoplankton, and their concentration decreases to the lake's average value of 0.04 mg/L.

During the summer stratification, the $\text{NO}_3\text{-N}$ content decreased to < 0.01 . $\text{NH}_4\text{-N}$ was constantly present in the water at $0.06\text{--}0.10$ mg/L (see Tables 5, 6). This means that where the oxygen saturation in the water column is $90\text{--}102\%$, a decrease in $\text{NO}_3\text{-N}$ concentration to zero does not indicate its total disappearance, but only a lag in the rate of nitrification from the rate of its assimilation by plankton.

Surveys in the relatively warm autumn of 2021 also recorded an absence of $\text{NO}_3\text{-N}$ in the lake water, with the exception of the area around trout cages (see Tables 5, 6). The concentration of $\text{NH}_4\text{-N}$ in the lake in 1971–1992 and 2001 varied from 0.01 to 0.13 mg/L (0.05 mg/L on average).

In winter, ammonium ions did not accumulate in the lake because of active ammonium nitrogen oxidation by nitrifying bacteria taking place in parallel with the ammonification process. The environmental conditions (O_2 content $9\text{--}11$ mg/L, $\text{pH} \approx 7$) promoted the oxidation of ammonium ions to nitrites. During the growing season, the level of ammonium ions in the lake was mainly controlled by the ratio of several processes: ammonification, assimilation, nitrification, and denitrification. In spring, the river and stream mouth areas and areas around trout cages were richer in NH_4^+ ions (up to 0.12 mg/L) than the central lake areas, where they were actively consumed by the growing spring phytoplankton.

During the summer, ammonification processes predominated in the lake. Ammonium nitrogen was formed as a result of the destruction and mineralization of autochthonous OM. Its maximum in summer was up to 0.10 mg/L.

The distribution of ammonium ions by depth in summer and winter was uneven. Their maximum was found near the bottom in the deep-water parts of the lake, where hypoxia was detected, and their diffusion from bottom sediments was underway.

The predominant form of nitrogen in Lake Vendyurskoe throughout the year is organic nitrogen (see Table 5). Its concentration in water in 2021–2023 fluctuated within $0.12\text{--}0.51$ mg/L (0.29 mg/L on average). Organic nitrogen during the periods of spring and autumn overturn was 67 and 80% , in the winter and summer – 65 and 87% of the total nitrogen. During the phytoplankton bloom, the surface layers of water got enriched with organic nitrogen (up to 0.5 mg/L). The average annual concentration of N_{org} in the lake water was 0.42 mg/L.

The features of the intra-annual circulation of nitrogen compounds ($\text{NH}_4^+ \rightarrow \text{NO}_2^- \rightarrow \text{NO}_3^- \rightarrow \text{N}_{\text{org}}$) in Lake Vendyurskoe are consistent with the patterns established for the water bodies of Northwest Russia. In particular, the reported turnover time for nitrogen compounds in the summer in lakes of Karelia is 1.8 days (Ryzhakov et al. 2010; Ryzhakov 2020).

Iron enters the lake with river runoff, mainly in the form of organo-mineral compounds, and with groundwater discharge. In 1971–1992 and 2001, the average concentration of total iron in water was $0.15\text{--}0.17$ mg/L, rising to $0.36\text{--}0.38$ mg/L during freshets. In the recent study period, total iron content in the lake water varied from $0.11\text{--}0.45$ mg/L (0.34 mg/L on average). A slight increase in the concentration of iron in the lake water may be due to the different methods of Fe (III) analysis as well as to an increase in the nutrient load on the lake.

The main source of dissolved silicon for the lake is river runoff. The content of dissolved silicon in the lake water in 1971–1992 and 2001 ranged from 1.5 to 2.3 mg/L (an average of 2.0 mg/L) (Kharkevich and Kryukova 1981; Ryzhakov et al. 2010). In 2021–2023, the concentration of dissolved silicon varied within $0.1\text{--}1.9$ mg/L, with its highest level found in the mouth of the Rindozherka River. Its average annual content in 2021–2023 was 1.2 mg/L, and the autumn average was 0.1 mg/L, which is 10 times lower than in the past. Field and experimental studies have demonstrated that silicon consumption by algae depends on the supply of phosphorus compounds in the water body (Dillon and Rigler 1974; Raspletina and Susareva 2002). In autumn, when silicon in Lake Vendyurskoe is actively consumed by diatoms and removed from the cycle, the river runoff cannot replenish the reserves. The decrease in silicon concentration in the lake water over the 50 -year period has been due not to a decrease in exogenous input, but to the intensification of biological processes in the lake. The trophic status of the lake based on the phytoplankton development criterion has changed from oligotrophic in $1973\text{--}1984$ to mesotrophic in $2007\text{--}2020$ (Sabylina and Basov 2003; Ilmast et al. 2008; Slastina et al. 2022). Consequently, the decrease in silicon content in the lake water can be considered as one of the consequences of eutrophication.

CONCLUSIONS

The ecosystem of Lake Vendyurskoe, formed as a result of the interaction of multiple natural processes in the aquatic environment and in the catchment area (forest drainage in $1971\text{--}1986$), is currently impacted by trout farming and changes in the regional climate of Karelia. The lake water exhibits low mineralization (15.6 mg/L on average). Noticeable changes over the 50 -year period have occurred in the ionic composition of the water: in 2021–2023, the content of sulfate ions dropped by 4 times compared to $1971\text{--}1985$, which may be due both to cessation of amelioration and a reduction in the concentration of sulfates in precipitation. Chloride

ions have decreased by half. An inverse correlation was revealed between the concentration of bicarbonates in the lake water in summer and the amount of atmospheric precipitation in the preceding winter-spring period. In the past 50 years, the amount of precipitation in southern Karelia has increased (by 65–80 mm from November of the previous year to July of the current year), creating the preconditions for a reduction in the concentration of bicarbonates in the lake water in the summer.

The lake water contains significant amounts of organic matter. The water color is 40 mg Pt-Co/L. The COD_{Mn} value is high (7.5 mgO/L on average).

The seasonal dynamics of nutrients in the lake have changed significantly, which is an indicator of an increased anthropogenic impact on the lake. A tendency towards an increase in the total phosphorus content in the lake's water over the 50 years (both in the surface and bottom layers) was revealed. During the summer stratification in the deep-water parts of the lake and near trout cages, inorganic phosphorus is mobilized from bottom sediments into the water under hypoxia conditions, and an endogenous phosphorus load builds up. This can stimulate an increase in biological productivity regardless of the amount of mineral phosphorus arriving from the catchment area.

The effect of air temperature on the duration of hypoxia at the bottom was revealed. The longest periods of hypoxia typically occurred in hot summer months (up to 30–46 days) and long winters (110–167 days) with early ice-on and late ice-off. The correlation between the duration of hypoxia in summer and air temperature in summer months suggests that the ongoing warming of the regional climate will deteriorate the oxygen conditions in the lake in summer. Longer hypoxia will be a factor for increased mobilization of mineral phosphorus and elevation of the phosphorus load. A rise in air temperature in autumn and spring, on the contrary, will help improve the oxygen conditions, as the period of hypoxia in winter will be reduced due to later ice-on and earlier ice-off.

The observed climatic variability and constant exposure to anthropogenic impact may affect the quality of the lake water in the near future. Having identified changes in the water's chemical composition, we managed to identify the zones of greatest risk in the lake (trout farm, deep-water areas). The findings can serve as reasoning for reducing trout farming volumes.

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ASSESSMENT OF LAND POTENTIAL FOR FOOD CROP DEVELOPMENT IN THE KARST LANDSCAPE OF GUNUNGSEWU HILLS, INDONESIA

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ABSTRACT. Gunungkidul region in Indonesia, though considered arid and agriculturally limited, has shown notable productivity in food crops, especially upland rice, cassava, groundnut, and maize cultivation. Main challenges of agricultural development in this region are limited accessibility to land due to its hilly and steep topography, as well as water scarcity. Accurate land-use planning tools are needed to allocate land resources to support regional agricultural activity. Therefore, a systematic assessment of land potential for food crop agriculture is needed using geoinformation techniques to enable well-planned development. This study segmented research area into doline units as mapping units. Accessibility, soil, and water factors were employed in evaluating land potential classes. The Analytical Hierarchy Process (AHP) method was used to determine the weights of parameters and parameter classes scores for each factor. Potential of dolines for food crop agriculture in Gunungkidul was assessed using 10 parameters including distance from road, distance from settlements, area of doline's valley, ratio of valley's area and doline's area, soil depth, soil texture, pH, Soil Organic Matter (SOM), Cation Exchange Capacity (CEC), and uppermost rock. Among these parameters, distance from roads (weight: 0.26), distance from settlements (weight: 0.20), and doline valley area (weight: 0.14) were identified as the most significant accessibility factors. Results indicated that 52% of the karst and karstic areas of Gunungkidul, characterized by arid hills, have potential for food crop agriculture development. This study provides valuable insights for policymakers and stakeholders aiming to promote sustainable agricultural systems in karst landscapes more broadly in arid regions.

KEYWORDS: agriculture, doline, food crop, karst, Gunungsewu hills

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INTRODUCTION

Food is the most essential basic need for human survival. Food security refers to the state where food is consistently available, easily accessible, safe for consumption, and affordable (Ahmad et al. 2021). Population growth is directly proportional to the increasing demand for food. Contrarily, food production is highly dependent on natural conditions and the availability of agricultural land. Certain food commodities can only be produced under specific natural conditions. This condition makes critical lands like Gunungkidul prone to food crises due to the limited range of agricultural commodities grown for household food production.

Small farmers make up about 70% of Gunungkidul's population. Most farmers face numerous challenges due to dry lands from its karst topography. Water shortages and bad soil quality make it hard for traditional farming to thrive, which slows down the area's economic growth (Antriyandarti et al. 2022). Dependence on food crops makes households highly vulnerable to fluctuations in agricultural yields, which can lead to food insecurity (Christanti et al. 2023). This condition also contributes to structural poverty in Gunungkidul.

Dolines are distinctive geomorphological features in karst landscapes that regulate the movement and distribution of water and air, shaping local conditions such as soil moisture, depth, temperature, and humidity. Their structure enables water accumulation, storage, and efficient drainage, which supports vegetation growth and helps reduce flood risks (Damayanti et al., 2025). Ecologically, dolines function as important microhabitats and refuges, promoting biodiversity, vegetation development, and organic carbon absorption (Valjavec et al., 2022). Typically, the land at the bottom of dolines (doline valleys) holds potential for agricultural development due to relatively thicker soil layers. Much organic matter builds up at the bottom of dolines, which makes the soil very healthy. Optimal utilization of doline valleys for agriculture can increase land productivity in karst areas, which are generally less fertile.

Assessing land potential in doline valleys is urged for optimal agricultural production. Doline valleys are sediment and organic material accumulation zones transported by erosion, creating thicker soils with better fertility than slopes or other karst plains. However, the hilly topography makes them difficult to access. The diverse dimensions of doline valley in Gunungsewu Karst form varying valley sizes, which must be considered in the assessment. Evaluating the land potential for agriculture facilitates the achievement of sustainable agriculture (Vaghela et al. 2018).

Assessing doline valley's potential for agricultural development involves integrating various criteria, which can be effectively achieved through Multi-Criteria Decision-Making (MCDM) techniques. MCDM aims to predict land potential for various applications, including agriculture. In the land potential assessment process using MCDM techniques, the AHP is adopted to estimate and assign weights in the MCDM process. AHP addresses complex decision-making processes involving various criteria, scenarios, and factors. AHP involves structuring multiple-choice criteria into a hierarchy, assessing the relative importance of each criterion, comparing alternatives for each criterion, and determining the overall ranking of alternatives (Everest et al. 2021). Integrating AHP analysis in Geographic Information Systems (GIS) provides robust and efficient spatial decision-support information.

The study is expected to produce a spatially explicit assessment of agricultural land potential in karst areas by delineating doline units and integrating accessibility, soil, and water factors using AHP-GIS methods, hereinafter referred to in this paper as the ASW Approach. It aims to identify and quantify the proportion and distribution of land suitable for food crop development, particularly highlighting areas with high, moderate, and low potential. Notably, the findings are expected to assist Gunungkidul stakeholders in boosting land productivity, the local economy, and food security. The study's objectives align with the Sustainable Development Goals (SDGs), particularly Goal 1 (no poverty), Goal 2 (zero hunger), Goal 10 (reduced inequalities), and Goal 11 (sustainable cities and communities).

MATERIALS AND METHODS

Study area

This study was conducted in the Gunungsewu Karst area in Gunungkidul Regency in the Special Region of Yogyakarta Province (7°46' - 8°09' S and 110°21' - 110°50' E) as shown in Figure 1. The topography of Gunungkidul is highly diverse, ranging from hills and valleys to caves formed by limestone dissolution. Geographically, Gunungkidul Regency is situated in the southeastern part of Special Region of Yogyakarta Province, bordering the Indian Ocean to the south. Gunungkidul Regency experiences a monsoonal climate, with the rainy season occurring from October to April, receiving an average annual rainfall exceeding 2,000 mm. The dry season spans from May to September and is characterized by minimal or absent rainfall. The average temperature is approximately 27°C, accompanied by high humidity during the rainy season.

Gunungsewu Karst area which belongs to the the Southern Mountains of Java and was formed through tectonic uplift since the Late Pliocene, producing a well-developed tropical karst landscape. The geology is dominated by thick Neogene limestone of the Wonosari-Punung Formation, consisting of reef and bedded limestones overlying older volcanic and volcanoclastic formations. Structurally, the area is influenced by tectonic compression that generated fractures and faults, controlling both karst development and subsurface drainage systems. As a result, Gunungsewu karst area exhibits advanced karstification characterized by cone karst morphology, dolines, underground rivers, and limited surface water due to dominant subsurface hydrological processes.

To further support the geological characterization of the study area, the spatial distribution and field identification of uppermost rock formations are also presented. The uppermost rock layer plays a significant role in controlling surface water retention and infiltration processes, which are critical in karst environments. In the Gunungsewu Karst area within Gunungkidul Regency, variations in lithology such as coral limestone and marly tuffaceous limestone influence the development of dolines and the hydrological behavior of the landscape. These lithological differences determine the permeability and storage capacity of the subsurface, thereby affecting the availability of water for agricultural use. Figure 2 presents the geological map of the study area, while Figure 3 illustrates the uppermost rock identification, including representative field conditions of marly tuffaceous limestone and coral limestone.

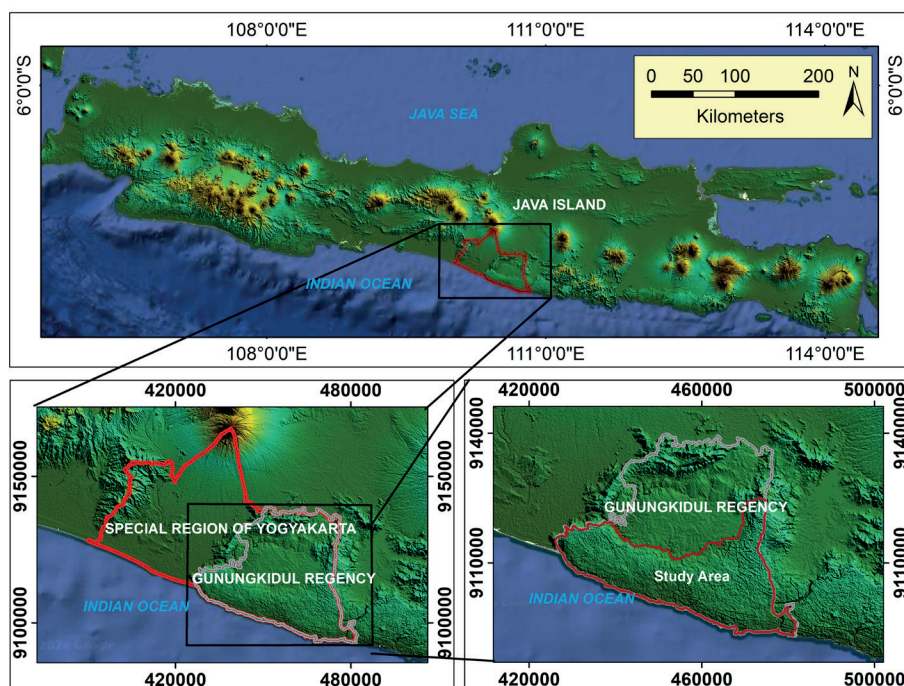


Fig. 1. Study area

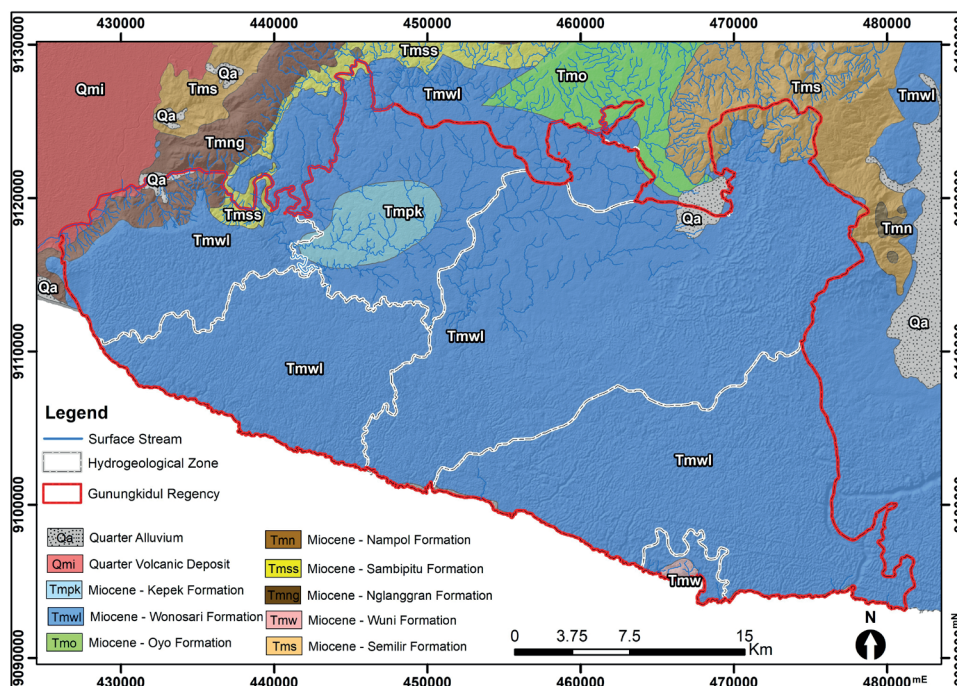


Fig. 2. Geological map of study area

ASW-approach and data collection

ASW (Accessibility-Soil-Water) is a framework designed to assess agricultural land potential within dolines in karst landscapes by considering accessibility, soil characteristics, and the capacity of the uppermost rock to retain water. The first factor, accessibility, assesses at how close land is to important amenities like roads and settlements. This element also determines the doline valley's agricultural carrying capacity by comparing it to its catchment. The second factor, soil, examines the suitability of soil characteristics for the dominant food crops in Gunungkidul. This assessment includes physical and chemical properties such as thickness, texture, cation exchange capacity (CEC), pH, and soil organic matter (SOM). The third factor, water, focuses on the ability of the uppermost rock to retain water, particularly in water storage in reservoirs or ponds. Karst's porous structure and rapid infiltration make the rock with the highest ability to

hold surface water vital for agriculture, especially in the dry season. This study examines rock types' capacity to maintain sustainable reservoirs for irrigation under water scarcity. Figure 4 illustrates the workflow of the study, including the methodological steps and the input data used.

Digital Elevation Model (DEM) data comes from 1:25,000 Indonesian Topographic Map's (RBI) contour data. Relief roughness interpretation was based on the Terrain Ruggedness Index (TRI), reclassified into three categories: rough (A), moderately rough (B), and smooth (C). The hydrogeological zone map was obtained from the study by Haryono et al. (2023). Furthermore, the hydrogeological zones are divided into five zones: Panggang (1), East (2), Bribin-Baron (3), Volcanic (4), and Ponjong (5). Capital letters and numbers were used to classify the study region into landform units with similar relief and hydrogeological characteristics. Finally, the study area was classified into 13 landform units as shown in Figure 5.

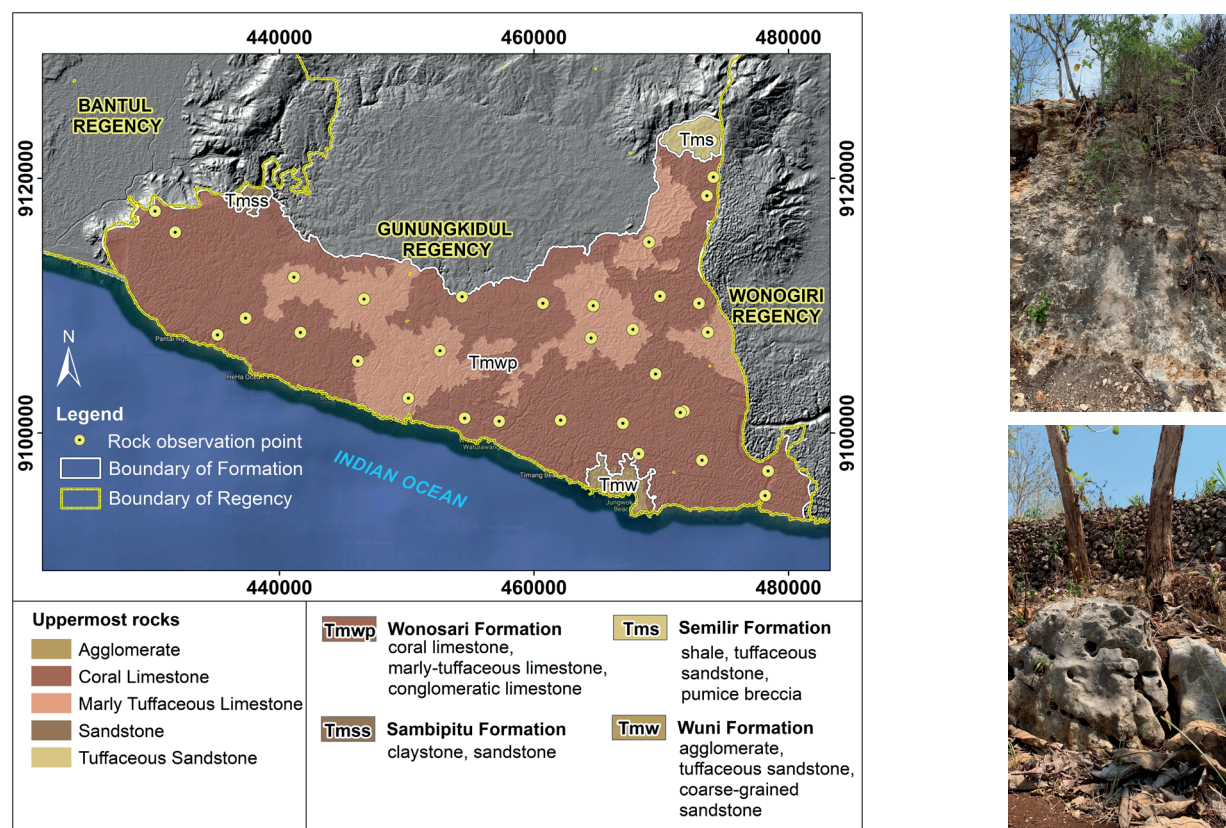


Fig. 3. Uppermost rocks identification map (a); marly tuffaceous limestone (b); coral limestone (c)

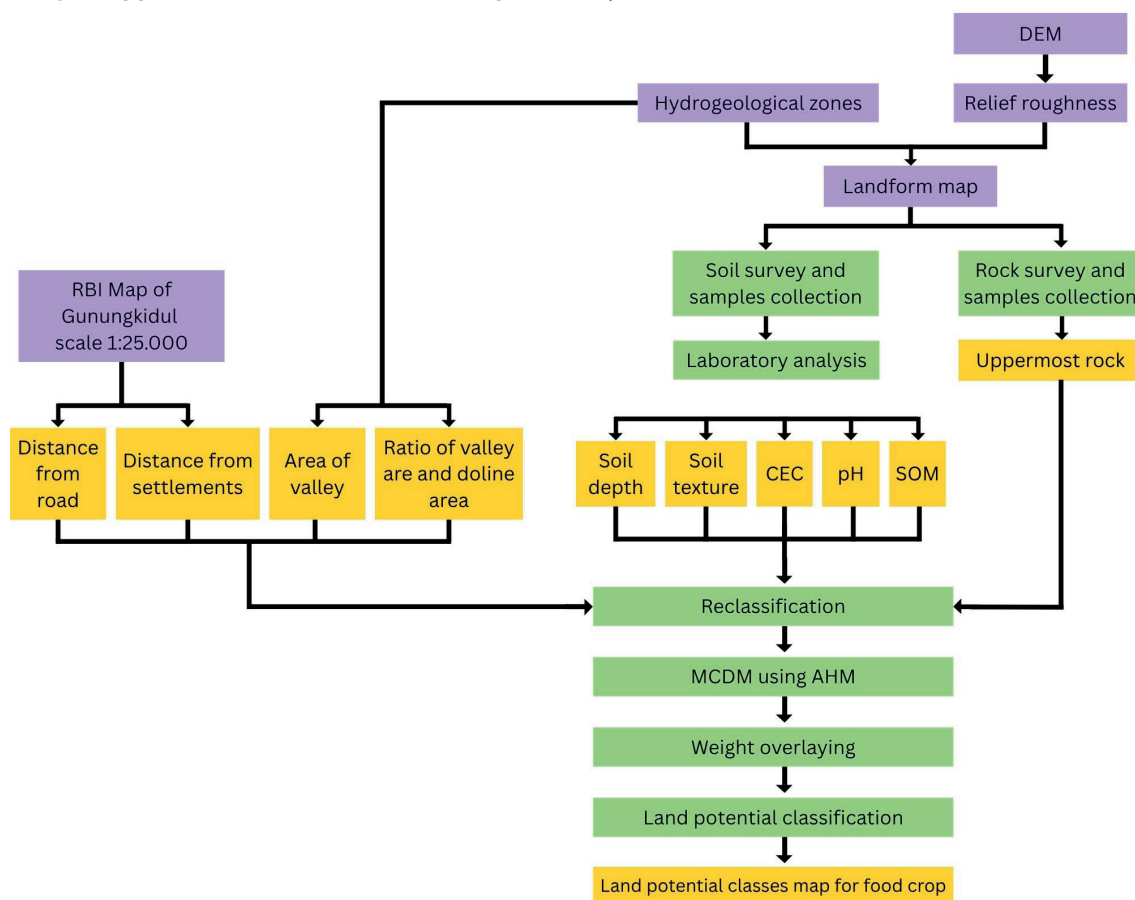


Fig. 4. Flowchart of the study methodology and input data

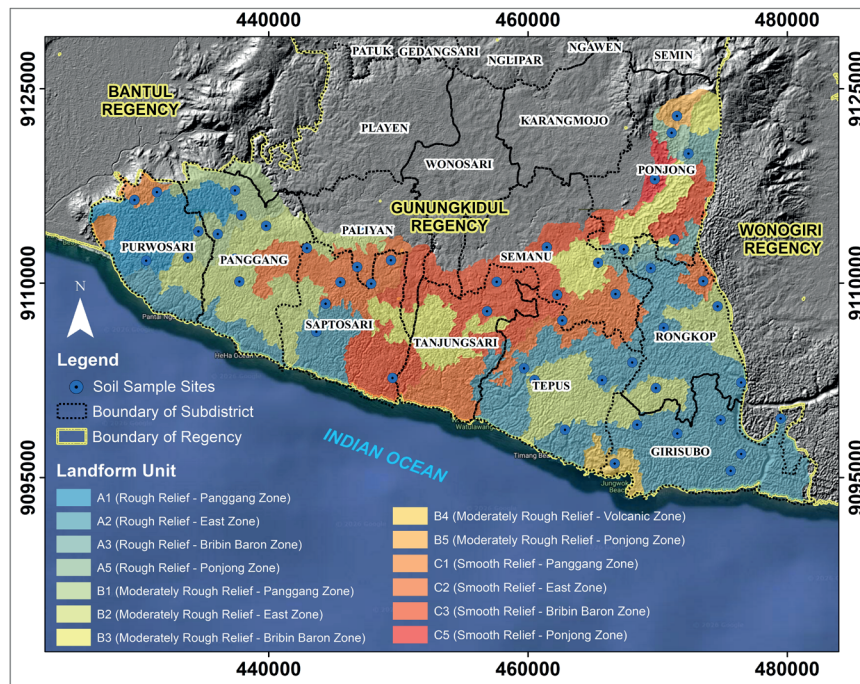


Fig. 5. Landform unit (a); doline valley (b); soil profile (c)

This study employed the watershed algorithm to delineate dolines or closed depressions. Hilltop data were extracted from a 6.25-meter resolution DEM using the terrain analysis function available in SAGA 9.3.1 software. Manual digitization was performed using ArcGIS 10.8 software at a 1:50,000 scale. 2,725 dolines or depressions were identified and subsequently used as mapping units.

Fieldwork involved the observation of land characteristics and soil sampling. Observation points and soil sampling were conducted through purposive sampling at each landform unit. Soil samples were collected to a depth of one meter or until bedrock was reached. Samples were brought to the lab in plastic bags for physical and chemical analysis. The chemical characteristics considered were pH, CEC, and soil organic matter (SOM). Its texture was part of its physical characteristics. Soil depth was recorded during field soil characterization. Laboratory analysis followed the technical guidelines for soil sample testing outlined by the Soil and Fertilizer Instrument Testing Center (Eviati et al. 2023).

Generating land potential map using AHP and GIS

Each data vector is classified into three classes: high potential (P1), moderate potential (P2), and low potential (P3) for food crop development. Reclassified criteria indicate how

different suitability levels for each criterion are distributed both spatially and geographically. The weighting of parameters and parameter classes was performed using AHP, which compares one parameter with another or one class with another using a pairwise comparison matrix (PWCM), as explained by Saaty (2014). Nine types of relationships between criteria were used in this method, defined on a scale from one to nine. These relationships represent the relative importance between criteria (Everest et al. 2021). As the scale increases, the criterion gains greater importance relative to its counterpart (Insani, 2023). In the PWCM, the importance of parameters was decided by considering the opinion of experts. The PWCM value for each parameter is mentioned in Table 1.

AHP mathematical model calculates the relative weights of criteria and the scores for alternatives through eigenvector methods. The eigenvector corresponding to λ_{max} represents the underlying standard scale and thus ranks each element in the ratio matrix (Nungula et al. 2024). The consistency of the parameter weights was evaluated by calculating the consistency ratio (CR). Consistency Ratio (CR) is calculated using (Equation 1). During the assessment, the evaluation matrix is considered consistent only if its ratio is < 0.1 .

$$CR = \frac{CI}{RI} \quad (1)$$

Where CI = Consistency Index; RI = Random Index. The Consistency Index (CI) value is calculated using the eigenvalue (λ_{max}) obtained from the AHP calculator and the number of parameters (n) from the AHP calculator. Random Index (RI) is simply obtained from the Random Index table provided by Saaty [16] as mentioned in Table 1.

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (2)$$

In creating the doline potential map for food crop agriculture, the reclassified layers, including accessibility, soil, and water criteria, covering ten parameters, were scored and weighted through AHP and integrated into the ArcGIS environment. The weighted layers for each parameter were overlaid using the weighted overlay analysis tool (Equation 3), where P = potential value; W_i = weight of the i -th parameter; X_i = class score of the i -th parameter; n = number of parameters.

$$P = \sum_{i=1}^n W_i X_i \quad (3)$$

RESULTS

Accessibility Potential

Distance from the road has the highest weight among the land potential class assessment parameters, with

a value of 0.26, followed by distance from settlements with 0.20 and the area of the doline valley with 0.14 as stated in Table 5. These three parameters belong to the accessibility criterion. Figure 6 shows the distribution of accessibility parameter maps. Karst regions generally feature rugged terrain with hilly topography and isolated doline depressions. Proximity to roads and settlements facilitates farmers in monitoring and maintaining the land regularly, thus increasing the potential for optimal harvest yields compared to lands that are difficult to access.

Distance from the road is crucial in assessing land potential for agriculture in the basins of dolines in karst areas, as physical accessibility to the land affects the ease of transportation for agricultural activities. The distance of land from roads can influence the efficiency of agricultural activities. Land close to main roads facilitates farmers in transporting tools, seeds, fertilizers, and harvests and accelerating product marketing. In karst and karstic areas, poor accessibility due to steep topography can increase transportation costs and hinder production efficiency. Therefore, the distance from roads can serve as an important indicator in evaluating the feasibility of land for agricultural development.

Distance from settlements is another critical parameter in the accessibility criterion. Farmers may access property near settlements faster, decreasing travel time and making daily agricultural monitoring easier. Land nearer to settlements is considered to have more potential due to its

Table 1. Random Index (RI)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

Table 2. AHP pairwise comparison matrix

	Distance from road (m)	Distance from settlements (m)	Area of doline valley (ha)	Ratio of doline area and valley area	Soil depth (cm)	pH	Soil texture	SOM (%)	CEC (cmol)	Uppermost rock	Weightage	CR < 0.1	CI
Distance from road (m)	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	8.00	1.00	0.26	0.07	0.11
Distance from settlements (m)	0.50	1.00	2.00	3.00	4.00	5.00	6.00	7.00	7.00	2.00	0.20		
Area of doline valley (ha)	0.33	0.50	1.00	2.00	3.00	4.00	5.00	6.00	6.00	1.00	0.14		
Ratio of doline area and valley area	0.25	0.33	0.50	1.00	2.00	3.00	4.00	5.00	5.00	2.00	0.11		
Soil depth (cm)	0.20	0.25	0.33	0.50	1.00	2.00	3.00	4.00	4.00	1.00	0.07		
pH	0.17	0.20	0.25	0.33	0.50	1.00	2.00	3.00	3.00	1.00	0.05		
Soil texture	0.14	0.17	0.20	0.25	0.33	0.50	1.00	2.00	2.00	1.00	0.04		
SOM (%)	0.13	0.14	0.17	0.20	0.25	0.33	0.50	1.00	1.00	1.00	0.03		
CEC (cmol)	0.13	0.14	0.17	0.20	0.25	0.33	0.50	1.00	1.00	1.00	0.03		
Uppermost rock	1.00	0.17	1.00	0.50	1.00	1.00	1.00	1.00	1.00	1.00	0.07		

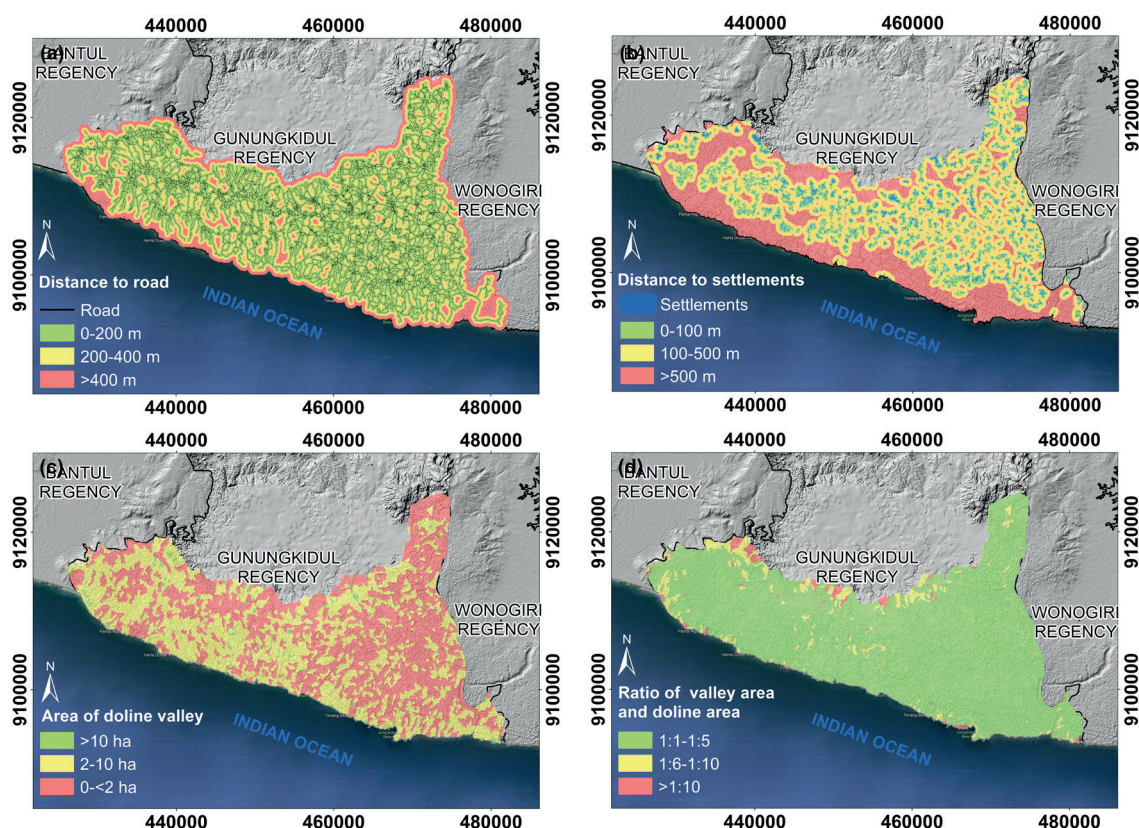


Fig. 6. Spatial distribution of: distance from road (a); distance from settlements (b); doline valley area (c); ratio of valley area and doline area (d)

ability to improve labor efficiency and safeguard harvests. Additionally, closeness to settlements allows land to be used as food crop fields for local consumption. Something else that is highly significant is the area of the doline valley, which shows how much land is open for farming. Differences in the dimensions of dolines and limestone hills allow for variations in the size of doline valleys. A sufficiently large doline enables more flexible and diverse land management, such as crop rotation or intercropping. Larger dolines have more significant potential to increase crop productivity and land use efficiency.

The ratio between area of doline valley and total doline area provides insight into the proportion of relatively flat land suitable for intensive agriculture. A lower ratio indicates that valley area is large enough for agriculture. Large land area correlates with agricultural production outcomes and land productivity. In other words, the agricultural inputs and labour invested in cultivation can yield profitable outputs. Furthermore, the ratio of doline valley area to the total doline area was classified into three classes: highly potential (P1) ranging from 1:1 to 1:5, moderately potential (P2) ranging from 1:6 to 1:10, and low potential (P3) with ratios greater than 1:10. The study area is predominantly

classified as highly potential. The characteristics of class P1 include relatively flat valley areas close to the doline's size, enabling the use of mechanical tools, and low erosion potential.

Soil properties potential

Soil is a fundamental component in the cultivation of food crops. The selection of suitable crops for cultivation on land with various limitations determines the land's productivity value and the income generated from agricultural activities. However, the soil assessment factors were tailored to the food crops grown in Gunungkidul. Cassava remains a leading food crop in Gunungkidul, as nearly the entire region is suitable for cassava cultivation. Other commodities such as upland rice, groundnut, and maize are significant crops widely cultivated by the local community in Gunungkidul. Table 3 shows the suitability class of soil parameters for each food crop that is predominantly cultivated in Gunungkidul.

Following the evaluation of food crops predominantly cultivated in Gunungkidul Regency and their soil suitability characteristics presented in Table 3, it is also important

Table 3. Land potential classes for each food crop commodity

Food crop commodity	Soil depth (cm)			Soil Texture			CEC (meq/100g)			pH			SOM (%)		
	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3	P1	P2	P3
Rainfed rice	>50	40-50	25-40	Fine	Fine	Coarse	>16	<16		5.5-8.2	5.0-5.5	<5	>1.5	0.8-1.5	<0.8
Cassava	>50	20-50	10-20	Fine	Fine	Coarse	>16	<16		6.0-8.2	5.6-6.0	<5.6	>0.4	<0.4	
Maize	>60	40-60	25-40	Fine	Fine	Coarse	>16	<16		5.5-8.2	5.3-5.5	<5.3	>0.4	<0.4	
Groundnut	>75	50-75	25-50	Fine	Fine	Coarse	>16	<16		5.6-7.6	5.4-5.6	<5.4	>1.2	0.8-1.2	<0.8

Source: Djaenudin et al. (2011) modified

to understand how these soil properties relate to the actual distribution of agricultural activities across the region. Land Use and Land Cover (LULC) analysis provides additional insight into current land utilization, particularly in identifying areas dominated by food crop cultivation such as cassava, maize, upland rice, and groundnut. By integrating soil suitability with existing land use patterns, this approach helps to better interpret the alignment between land potential and agricultural practices in the study area. Furthermore, the LULC map enables a clearer visualization of the spatial distribution of food crop commodities, thereby supporting a more comprehensive assessment of soil property potential. The Land Use and Land Cover map of the study area is presented in Figure 7.

Soil texture directly influences soil aeration and its ability to retain and absorb water. Analysis shows that the study area's soil texture is clay. Fine-textured soils in karst areas prone to drought play a significant role in water retention. Soil depth is crucial as it affects the availability of space for plant roots and the soil's capacity to retain water and nutrients. Most of soil depth in the Doline Valley at the study site is classified as deep (>50 cm) As presented in Figure 8, making it relatively suitable for food crop cultivation.

From a chemical perspective, CEC, pH, and SOM are critical to determining soil fertility and plant nutrient availability. Soil pH affects nutrient solubility, while SOM

provides a source of nutrients and improves soil structure. CEC indicates the soil's ability to absorb and supply essential nutrients to plants. Based on laboratory tests as displayed in Table 4, the pH, SOM, and CEC values at the study site are dominated by class P1, indicating that the soil has a high potential for supporting agricultural activities. Combining these three parameters ensures that the doline soils provide a chemical environment conducive to the growth of major food crops in the karst area.

To further support the interpretation of soil characteristics presented in Table 4, spatial visualization is essential to capture the variability of soil properties across the study area. Although the overall soil conditions indicate dominance of high-potential classes (P1), their distribution is not entirely uniform within doline units. Variations in soil depth, texture, and chemical properties such as pH, SOM, and CEC influence the spatial heterogeneity of land suitability for food crop development. Understanding these spatial patterns allows for a more precise identification of areas with optimal and suboptimal soil conditions, thereby improving the accuracy of land potential assessment. Figure 9 illustrates the spatial distribution of soil variables, providing a comprehensive overview of how these parameters are distributed across the landscape and their contribution to agricultural potential in the study area.

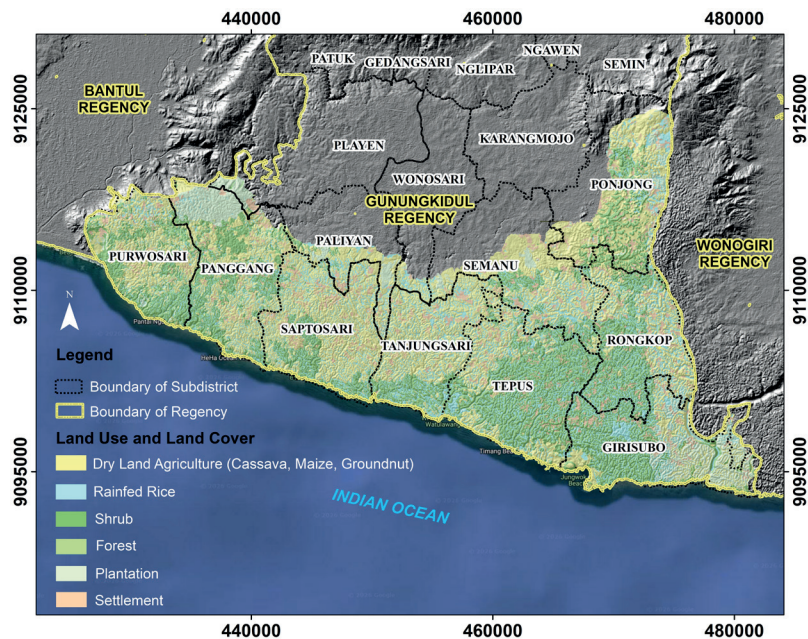


Fig. 7. Land use and land cover (LULC) map of the study area

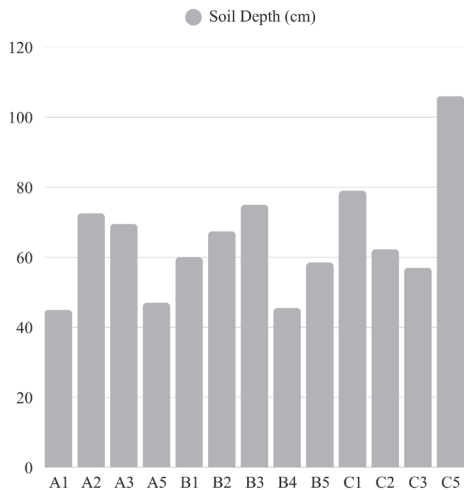


Fig. 8. Soil depth in research area

Table 4. Soil properties characteristic

Landform	Soil texture		CEC (meq/100g)		pH		SOM (%)	
	Class	Group	Value	Class	Value	Class	Value	Class
A1	Clay	Fine	36.87	High	7.75	Slightly alkaline	2.89	Medium
A2	Clay	Fine	24.04	Moderate	6.53	Slightly acidic	2.60	Medium
A3	Clay	Fine	27.40	High	6.45	Slightly acidic	2.08	Medium
A5	Clay	Fine	19.41	Moderate	5.30	Strongly acidic	3.19	Medium
B1	Clay	Fine	30.97	High	6.70	Neutral	2.06	Medium
B2	Clay	Fine	24.36	Moderate	6.80	Neutral	2.46	Medium
B3	Clay	Fine	14.33	Moderate	6.50	Slightly acidic	2.48	Medium
B4	Clay	Fine	28.92	High	7.20	Neutral	3.37	Medium
B5	Clay	Fine	25.04	High	6.00	Slightly acidic	2.83	Medium
C1	Clay	Fine	25.43	High	7.80	Slightly alkaline	1.76	Medium
C2	Clay	Fine	18.13	Moderate	7.09	Neutral	2.19	Medium
C3	Clay	Fine	26.71	High	6.38	Slightly acidic	2.41	Medium
C5	Clay	Fine	13.27	Moderate	6.50	Slightly acidic	2.44	Medium
Classification References	(Djaenudin et al. 2011)		(Diatta et al. 2014)		Islam et al. 2021)		Islam et al. 2021)	

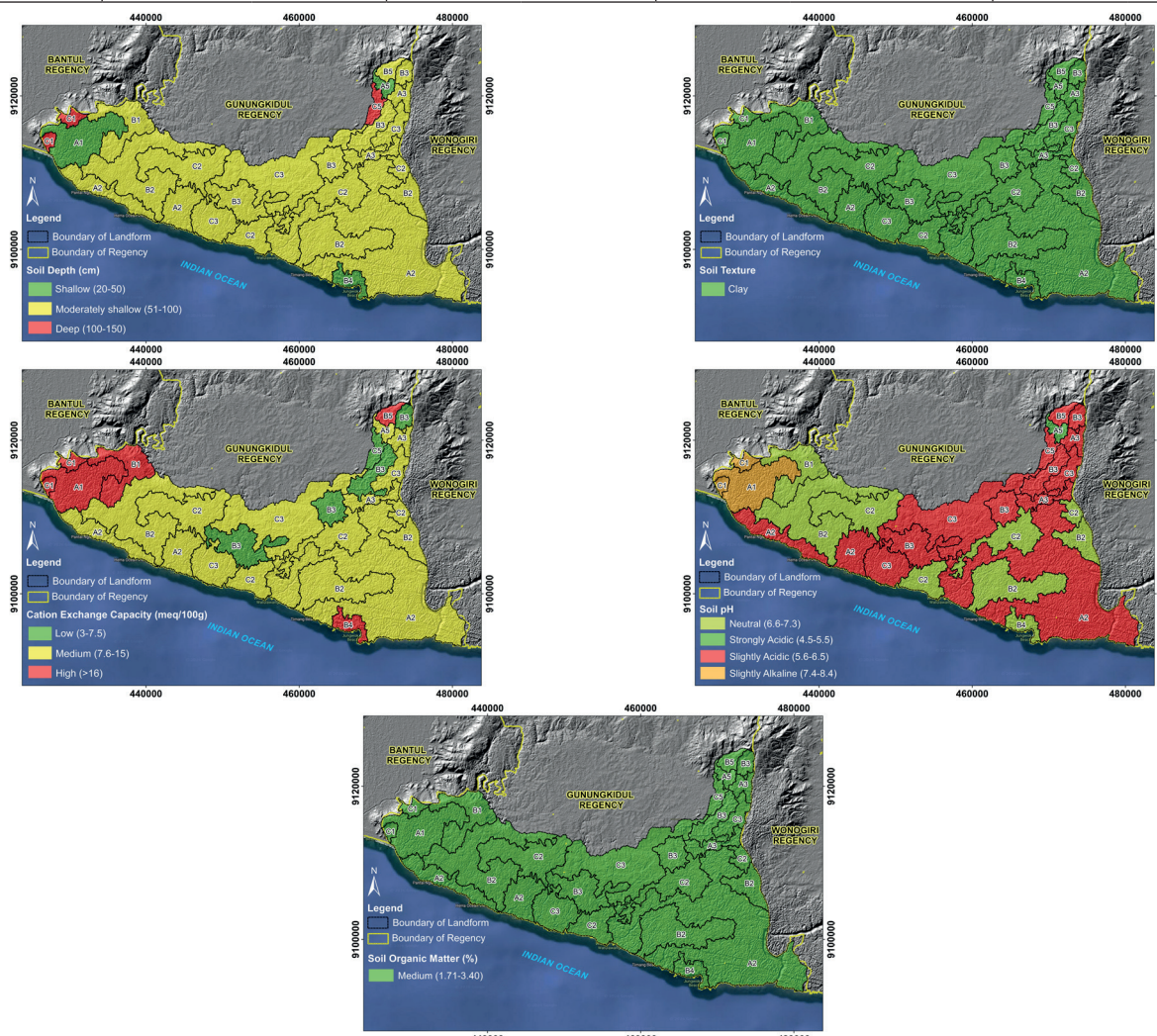


Fig. 9. Spatial distribution of soil variables: soil depth (a); soil texture (b); CEC (c); soil pH (d); SOM (e)

Water holding potential

Uppermost rock parameters are considered when assessing doline valley land potential for agriculture, presuming impermeable rock layers can store water and sustain micro-reservoirs for rainfall collection. Impermeable rocks do not contain water and cannot transmit it. The stratigraphy of rocks was predicted through the uppermost rock identification and the composition of the rocks forming each formation. Coral limestone stratigraphy over marly tuffaceous and conglomeratic limestone layers in the Wonosari Formation creates an optimum impermeable barrier for water retention. On the opposite, coral limestone at the base allows water to easily permeate the lower levels, causing leaks in micro-dams or ponds due to coral rocks' porous structure.

In the Wuni Formation, the stratigraphy of agglomerate over tuffaceous sandstone and coarse-grained sandstone creates a slightly impermeable layer. Although less effective than the rocks in other formations, this combination retains some surface water and supports rainwater harvesting through micro-reservoirs. This layer has lower porosity and permeability than others, making it suitable for micro-reservoir construction, though with more limited storage capacity. Further, in the Semilir and Sambipitu Formations, layers rich in tuffaceous sandstone, shale, and claystone are assumed to be effective in water retention. Tuffaceous sandstone in the Semilir Formation and claystone in the Sambipitu Formation create impermeable layers that strongly support the construction of micro-reservoirs at the base of dolines. These layers prevent seepage and allow more effective rainwater storage in regions prone to surface water retention difficulties. Figure 3 illustrates the distribution of uppermost rocks across each formation, derived from field observations.

Overall potential

The final map indicating land potential classes was created after all parameter weights and parameter class scores from the AHP matrix were integrated. Parameter

weights and parameter class scores of the AHP matrix are shown in Table 5. The doline potential map for agricultural development was created by summing the weighted scores for all parameters. The resulting maximum sigma and CR values were 0.64 and 0.07 below the allowed threshold, respectively.

The maximum sigma value was classified into three classes using the natural breaks (Jenks) function in ArcGIS software, resulting in classes as shown in Figure 10. The research findings indicate that 52% (13,032 ha) of the land at the base of the doline has high potential, 37% (9,232 ha) has moderate potential, and 12% (2,950 ha) has low potential. Doline areas with high potential are predominantly located in the central part of the study area, where road access is very convenient, and settlements are closely located.

The classification of land potential into high (P1), moderate (P2), and low (P3) categories reflects the integrated suitability of accessibility, soil characteristics, and water availability for food crop cultivation in Gunungkidul Regency. Areas classified as high potential (P1) exhibit favorable conditions across these parameters, including adequate road access, suitable soil physical and chemical properties, and relatively better water retention capacity. These conditions support the cultivation of major food crops such as rainfed rice, cassava, maize, and groundnut with relatively low operational constraints. In addition, high potential areas are generally associated with more stable geomorphological conditions within doline valleys, where thicker soil accumulation and gentler slopes reduce the likelihood of surface instability. Consequently, these areas not only offer higher agricultural productivity but also present lower relative risk for land degradation and subsidence compared to less suitable zones.

In contrast, moderate (P2) and low (P3) potential classes indicate increasing limitations that affect both cultivation suitability and land management feasibility. Moderate potential areas are characterized by partial constraints, particularly in terms of accessibility and seasonal water

Table 5. Classes score for every parameter

Criteria	Parameters	Parameter Classes	Potential Classes	Area (ha)	%	Scores	Weight	References
Accessibility	Distance from road (m)	0-200	P1	22,168	88	0.68	0.26	(Widiatmaka et al. 2016) modified
		200-400	P2	2,203	9	0.20		
		>400	P3	843	3	0.12		
	Distance from settlements (m)	0-100	P1	9,382	37	0.61	0.2	(Tanjung et al. 2021) modified
		100-500	P2	9,742	39	0.27		
		>500	P3	6,090	24	0.12		
	Area of doline's valley (ha)	>10	P1	14,589	58	0.54	0.14	(FAO, 2022) modified
		2-10	P2	10,458	41	0.30		
		0-<2	P3	166	1	0.16		
	Ratio of valley's area and doline's area	1:1-1:5	P1	24,450	97	0.54	0.11	Interpretation
		1:6-1:10	P2	678	3	0.30		
		>1:10	P3	85	0	0.16		

Soil	Soil depth (cm)	>50	P1	23,774	94	0.67	0.07	(Djaenudin et al. 2011) modified
		40-50	P2	1,440	6	0.33		
	pH	6-8.2	P1	24,923	99	0.67	0.05	
		5-6	P2	291	1	0.33		
	Soil texture	Halus	P1	25,214	100	0.67	0.04	
		Agak Kasar	P2	-	0	0.33		
	SOM (%)	>1.5	P1	25,214	100	0.67	0.03	
		0.8-1.5	P2	-	0	0.33		
	CEC (cmol)	>16	P1	22,874	91	0.75	0.03	
		0-16	P2	2,339	9	0.25		
Water	Uppermost	Coral Limestone	P1	18,032	72	0.28	0.07	Interpretation and survey
		Tuffaceous Sandstone	P1	385	2	0.28		
		Sandstone	P1	55	0	0.28		
		Agglomerate	P2	250	1	0.10		
		Marly Tuffaceous Limestone	P3	6,492	26	0.07		

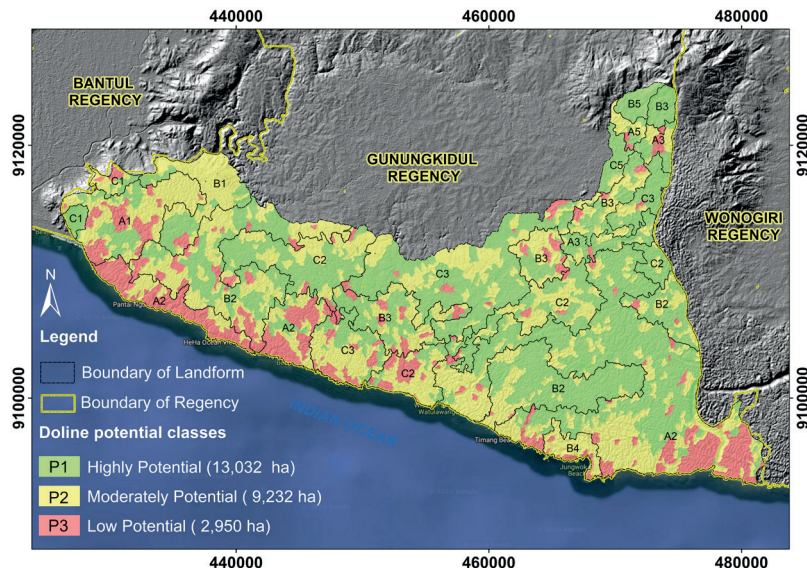


Fig. 10. Doline potential classes map

availability, which may reduce agricultural efficiency but can still be improved through infrastructural interventions such as road development and water management systems. Low potential areas, on the other hand, are typically located in more isolated dolines with steep surrounding terrain and limited connectivity, making access and resource distribution more challenging. Although these areas may possess relatively fertile soils, their limited water availability and difficult terrain increase the complexity of agricultural utilization and may elevate the risk of geomorphological instability if improperly managed. Across all potential classes, water scarcity remains a critical constraint in karst environments; however, this limitation can be mitigated through the construction of micro-reservoirs at water

accumulation points and the adjustment of cropping patterns in accordance with seasonal rainfall variability, thereby enhancing the practical applicability of land potential classifications.

DISCUSSION

Most of the study sites have a very high potential for agriculture, indicating that doline valley has significant potential for agricultural development despite facing several obstacles. Challenges in developing agricultural areas can be overcome through land modification efforts and increasing accessibility. Accessibility is a critical factor for agricultural development in Gunungssewu karst area,

where steep and hilly terrain complicates access to dolines, increasing production costs and reducing cultivation efficiency. Prioritizing road construction to isolated dolines can enhance land utilization, integrate agricultural areas with markets and distribution centers, and improve food security. Improved market access enables farmers to respond quickly to consumer demand, adapt to climate-induced uncertainties, and reduce post-harvest losses. This study aligns with the findings of Rahma Dayanti and Soetjipto (2024), who emphasize that farmers with reliable market access are better equipped to manage risks and adapt to evolving market conditions.

Doline valley tends to have thicker and more fertile soil layers than the slopes or other plains in karst areas. These deeper soil layers allow plant roots to absorb more water and nutrients, supporting plant resilience against drought and enhancing land productivity. This advantage makes the doline area a potential sustainable food crop development zone. With proper soil conservation techniques, doline land can be effectively managed to support main food crops such as upland rice, cassava, maize, and legumes. Soil conservation in dolines can be achieved through agroforestry and contour terracing, with tree planting on slopes anchoring the soil and regulating the microclimate (Cao et al. 2024). As one of the dominant vegetation types in Gunungkidul, teak trees can be planted on doline slopes for conservation purposes while simultaneously providing additional income for farmers. The findings of this study are consistent with Ribolzi et al. (2017), who demonstrated that teak plantations significantly influence overland flow and sediment yield, both of which are critical components of soil conservation efforts.

Water scarcity during the dry season can be addressed by modifying planting patterns and constructing micro-reservoirs. The construction of micro-reservoirs in doline valleys helps farmers access rainwater during the dry season through rainwater harvesting. Mganga et al. (2022) discuss how in situ rainwater harvesting techniques, including the use of micro-catchment can stabilize dryland landscapes and restore degraded areas, making them more productive. The placement of the reservoirs should focus on points of water flow accumulation to ensure their effectiveness as illustrated in Figure 11. The dimensions of the reservoirs are adjusted to the area of land and the crops to be cultivated. Local governments can assist with materials such as geomembranes to line the reservoirs, making them

impermeable, thereby allowing stored water to last longer and supporting irrigation activities in the surrounding areas.

In addition to infrastructure assistance, the government is also expected to actively monitor the climate and disseminate accurate weather forecasts to the community, especially in light of climate change, which affects weather patterns and planting seasons. Extension services and guidance to revise traditional practices such as *pranoto mongso*¹ with more scientific weather information will assist farmers in determining the appropriate planting time and selecting crops suited to current weather conditions. These efforts, alongside the development of infrastructure and the provision of irrigation facilities in doline valleys, are expected to improve food security and the local economy of communities in the karst area. Table 6 illustrates the modifications in food crop cultivation over a one-year period, considering the availability of water from rainfall.

Agricultural land potential assessments have been extensively studied; however, limited research has focused on evaluating agricultural potential in karst hill regions, which are often perceived as arid and infertile. Despite this perception, karst landscapes, particularly doline bases, exhibit significant potential for agricultural utilization, warranting further exploration. A key limitation of the current research lies in the exclusion of climate factors from the assessment framework. Climate considerations are critical to the viability and productivity of agricultural systems, particularly for rainfed crops such as rice, maize, cassava, and groundnut, as they significantly influence water availability, crop growth cycles, and overall agricultural sustainability. This omission limits the comprehensiveness of the assessment. Future studies should address this limitation by incorporating climate variables into the assessment framework, thereby enabling a more holistic evaluation and supporting more effective planning for agricultural development in karst landscapes.

CONCLUSIONS

In conclusion, 52% of the total study area, comprising 2,513 doline units, falls into class P1 (highly potential) for food crop agricultural development, 37% into class P2 (moderately potential), and 12% into class P3 (low potential). The utilization of areas with potential for agricultural development can involve the cultivation of food crops such as rice, cassava, maize, and groundnut.

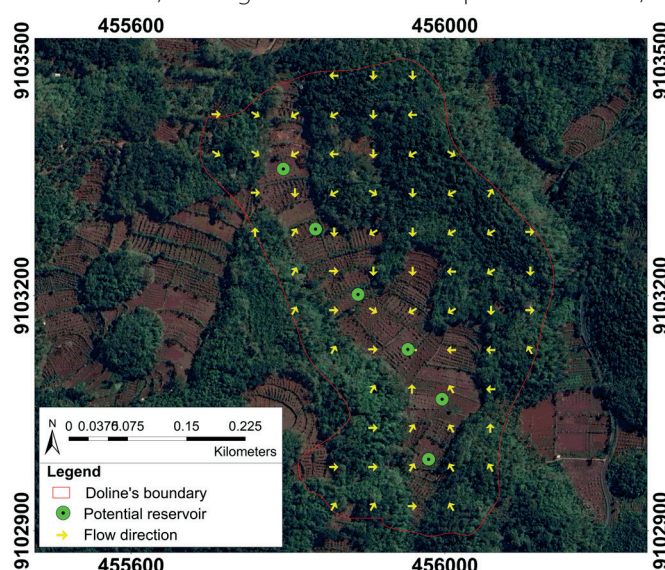


Fig. 11. Potential reservoir point

¹ Pranoto Mongso is a traditional Javanese concept of understanding seasonal and ecological cycles to guide agricultural practices, reflecting harmony with nature.

Table 6. Planting season modification of food crops

Month	JAN	FEB	MAR	APR	MAY	JUN	JUL	AGT	SEP	OCT	NOV	DEC
Monthly average rainfall (2012-2022)	410	299	313	195	87	115	37	25	43	172	337	361
Water Availability	320	216	231	126	23	54	-28	-57	-57	65	240	271
Type of month	WM	WM	WM	WM	DM	DM	DM	DM	DM	DM	WM	WM
Potential commodity	DR	MA, GN, CS	MA, GN, CS	MA, GN, CS	GN	GN	CS	CS	CS	MA, GN, CS	DR	DR

Type of month. WM – wet month; DM – dry month; Potential commodity. DR – Dryland rice, MA – Maize, CS – Cassava, GN – Groundnut. Note: red color indicates months when there is a water deficit

The success of crop production is highly dependent on the planting pattern, which is based on the availability of rainfall, particularly during the early stages of planting. Therefore, climate prediction becomes a key factor for ensuring successful crop growth. Water conservation practices aimed at capturing a portion of rainfall can serve as a safeguard to ensure harvest success. Despite providing a comprehensive assessment of agricultural land potential in the karst landscape of Gunungkidul Regency using ten

parameters, this study is limited by the inherent subjectivity of the AHP method, as the final results are highly dependent on the pairwise comparison and weighting assigned by key informants. Future research is recommended to incorporate additional assessment factors and develop alternative weighting scenarios or sensitivity analyses to improve the robustness and reliability of land potential evaluation in karst environments. ■

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ANALYSIS OF FOREST VEGETATION CHANGES IN VIETNAM'S CENTRAL HIGHLANDS AND SOUTHEAST REGIONS USING REMOTE SENSING AND MACHINE LEARNING

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ABSTRACT. Forest vegetation is pivotal for maintaining ecological equilibrium and providing essential ecosystem services, yet faces persistent decline, particularly in ecologically sensitive regions like Vietnam's Central Highlands and Southeast. This study aimed to assess the status and dynamics of forest vegetation across these regions from 2016 to 2024, providing a scientific foundation for sustainable forest management. Using Sentinel-2 imagery (10–20 m resolution), GIS, and a Random Forest classifier, we mapped 21 vegetation classes and assessed forest change in Vietnam's Central Highlands and Southeast regions for 2016–2024. The classifier achieved strong performance (mean precision = 0.81, recall = 0.78, F1 = 0.79). Results indicate a net decline in natural forest area (e.g., Rich evergreen broadleaf forest decreased by 2,166.5 ha; Medium coniferous forest decreased by 1,776.8 ha), while "Other lands" increased by 10,232.5 ha and grasslands/shrub/regenerated trees declined by 10,037 ha, reflecting substantial land-use conversion pressures. The study's novelty lies in a refined training-sample collection protocol and systematic hyperparameter optimization tailored to highly heterogeneous tropical vegetation and complex terrain, improving classification reliability for large, fragmented landscapes. These quantitative findings provide actionable evidence to support targeted forest management and land-use change mitigation measures. Urgent implementation of sustainable forest management practices and robust biodiversity conservation measures is imperative to protect these valuable forest ecosystems for future generations.

KEYWORDS: tropical forest, Sentinel-2, Random Forest, mapping, forest management, land-use change

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INTRODUCTION

Tropical rainforest vegetation is a cornerstone of global ecosystems, harboring approximately 50% of the planet's biodiversity and playing an essential role in climate regulation, ecological balance, water resource protection, and climate change mitigation (Denslow 1987, Ostendorf et al. 2001, Ghazoul et al. 2010). Despite covering approximately 11% of the Earth's land surface, tropical rainforests are disproportionately impacted by economic development, resource exploitation, deforestation, and climate change (Amelung et al. 1992, Ogboi 2001, Wan Mahari et al. 2020). Deforestation rates have accelerated in recent decades, driven by increasing demand for timber,

agricultural land, and urbanization (Kumar et al. 2022). Reports from the Food and Agriculture Organization (FAO) of the United Nations indicate an average annual global forest loss of approximately 10 million hectares, with a significant portion concentrated in tropical regions, including the Amazon (Binswanger 1991), the Congo Basin (Aquilas et al. 2022), and Southeast Asia (Turner et al. 2023).

Vietnam's Central Highlands and Southeast regions present a distinct combination of basalt-derived fertile soils, pronounced elevation gradients (with Central Highlands plateaus typically ~800–1,000 m), and a tropical monsoon climate (annual rainfall ~1,800–2,500 mm). These environmental gradients drive a mosaic of

forest types — including evergreen broadleaf, deciduous dipterocarp, mixed broadleaf–conifer, bamboo stands, and coastal mangroves — and create complex terrain and phenology-induced spectral variability that complicates remote sensing classification. Additionally, forest ecosystems in the Central Highlands and Southeast regions of Vietnam are subject to considerable pressure from illegal logging activities, forest fires, and the impacts of climate change, which threaten both biodiversity and ecosystem services (Tai et al. 2021, Dinh et al. 2023). Recent years have witnessed a growing application of satellite imagery, particularly Sentinel-2 data, for vegetation cover monitoring in this region (Nguyen et al. 2020, Huong et al. 2021). Results indicate that Sentinel-2 imagery offers superior classification accuracy, especially for distinguishing evergreen, semi-evergreen, and agricultural lands in mountainous terrain, primarily due to its fine spatial resolution (Thi Hoai et al. 2025). Furthermore, the integration of Sentinel-2 satellite data with Random Forest (RF) models has demonstrated advantages in tracking dynamic changes across various land cover types within the Central Highlands and Southeast regions of Vietnam (Do et al. 2025). These works demonstrate improved class separability at finer spatial scales but are often constrained by limited geographic extent, single-year analyses, or limited adaptation to topographic illumination effects. Few region-scale, multi-temporal assessments explicitly refine training-sample strategies and hyperparameter tuning to address spectral confusion and mixed-pixel problems across the heterogeneous, mountainous landscapes of the study area.

Faced with the growing need for continuous and comprehensive forest monitoring, traditional field-based methods are increasingly challenged by limitations in temporal frequency, spatial extent, and cost-effectiveness (Schnell et al. 2015). Consequently, modern remote sensing technologies are recognized for their superior capabilities in forest resource management (Hudak et al. 2009, Lechner et al. 2020, Ngo et al. 2024). Satellite-based platforms, such as Landsat (Raši et al. 2011), Sentinel (Erinjeri et al. 2018), and high-resolution commercial systems such as WorldView (Ferreira et al. 2021), and RapidEye (Gärtner et al. 2016), provide access to spatially explicit data at appropriate temporal resolutions, enabling near real-time or periodic monitoring of vegetation dynamics. These satellite images provide a wealth of information, including reflectance spectra, spatial resolution, and temporal resolution, facilitating the discrimination of vegetation types and the identification of deforestation, fire disturbances, and illegal logging activities (Dennis et al. 2005, Matricardi et al. 2010, Mujetahid et al. 2023). Furthermore, geographic information system (GIS) technologies enable the integration, processing, and analysis of spatial data to create zoning maps and classification models and simulate trends in forest changes (Pijanowski et al. 2002, Reddy et al. 2017). GIS plays a central role in combining remote sensing data with ancillary information such as ground truth data, field samples, and climate data, thereby facilitating more accurate assessments of forest status and vegetation dynamics within the study area (Weiers et al. 2004, Karan et al. 2016). The integration of remote sensing and GIS with machine learning techniques is emerging as a powerful approach to automating and enhancing forest monitoring capabilities, enabling accurate classification, change detection, and prediction of future forest conditions.

Machine learning techniques have revolutionized environmental monitoring, particularly in the classification and detection of forest change (Himeur et al. 2022, Yun et

al. 2024). Algorithms such as RF, support vector machines (SVMs), and convolutional neural networks (CNNs) demonstrate robust capacity for processing large volumes of image data, enabling the identification of characteristic spectral and spatial patterns associated with diverse vegetation types and land cover classes (Sothe et al. 2020, Sothe et al. 2020, Saim et al. 2025). These algorithms, through self-learning and model optimization, often yield higher classification accuracies than traditional methods do, minimizing classification errors and providing more precise predictive capabilities for assessing future change trends (Wang et al. 2025). Furthermore, the integration of satellite data services and cloud-based platforms, such as Google Earth Engine, has significantly reduced technical and logistical barriers, facilitating efficient access, processing, and analysis of large geospatial datasets for continuous monitoring, real-time mapping, and large-scale predictive modeling in support of sustainable forest resource management (Koskinen et al. 2019, Phalke et al. 2020, Jahromi et al. 2021). This combination of remote sensing, GIS, and machine learning offers a potentially scalable, cost-effective, and synoptic approach for monitoring forest resources across expansive and heterogeneous landscapes. While recent studies have primarily focused on smaller, specific areas, our research distinctly addresses the Central Highlands and Southeast regions. This area, characterized by unique ecological transitions and significant development pressures, has seen limited comprehensive, multi-temporal assessments utilizing Sentinel-2 data and RF models. In this study, we introduce a refined methodology for training sample collection and parameter optimization specifically tailored to the highly heterogeneous vegetation structures and complex terrain of these particular regions. This approach meticulously addresses challenges such as spectral confusion and inter-class variability often encountered in such diverse landscapes.

In Vietnam, particularly within the Central Highlands and Southeast regions, the application of remote sensing, GIS, and machine learning for forest monitoring remains underexplored. Specifically, there is a need for methodologies that closely integrate machine learning algorithms with remote sensing and GIS data to improve the efficiency and accuracy of classifying and forecasting vegetation changes under the diverse and complex terrain conditions characteristic of this region. Therefore, the objectives of this study are to (i) develop and validate a Random Forest classification framework tailored to the Central Highlands and Southeast using Sentinel-2 spectral bands, vegetation indices, and terrain variables; (ii) produce multi-temporal vegetation maps for 2016, 2020, 2021, and 2024 and assess classification accuracy; and (iii) quantify spatial–temporal transitions among key forest and non-forest classes to inform targeted forest management and land-use change mitigation. This study advances the regional remote sensing literature by (1) integrating multi-year Sentinel-2 MSI (2016–2024) with Random Forest classification across the full Central Highlands and Southeast regions, (2) implementing a refined protocol for stratified training-sample collection and systematic hyperparameter optimization to adapt the RF model to mountainous terrain and fragmented vegetation, and (3) delivering class-level area-change quantification for 21 vegetation/land-cover types aligned with national inventory cycles — thereby producing spatially explicit, policy-relevant evidence at a regional scale.

MATERIALS AND METHODS

Study area

The study area encompasses the Central Highlands and Southeast regions of Vietnam (Fig. 1). According to a 2025 report by the Vietnamese Ministry of Agriculture and Environment, the total area of the study region is approximately 78,000 km². Of this, the Central Highlands region has a total forest area of over 2.59 million hectares with a forest cover rate of 46.34%, making it a region with a large forest area. The Southeast region has a significantly smaller forest area, approximately 479,730 hectares, with a forest cover rate of 19.6%. The topography is characterized by a diverse mosaic of features, ranging from layered plateaus with average elevations of 800 to 1,000 m in the Central Highlands to coastal plains in the Southeast (Shinjo et al. 2024). These regions were specifically chosen for their ecological importance, showcasing diverse and unique forest ecosystems. Additionally, they play a crucial role in national development, which adds significant pressure on natural resources.

The regional climate is classified as a tropical monsoon regime, with distinct wet (May–October) and dry (November–April) seasons. The average annual rainfall ranges from 1,800 mm to 2,500 mm, with precipitation being primarily concentrated during the wet season. The mean annual temperature is approximately 24°C to 27°C, with minimal seasonal variation (Vu et al. 2015, Nguyen Duc et al. 2019). The soil types in this region are diverse,

with major classifications including ferralsols, greyzems, fluvisols, and arenosols. Ferralsols, derived from basaltic parent material, cover a substantial portion of the Central Highlands and are distinguished by their porosity, nutrient richness, and suitability for the cultivation of long-term industrial crops and natural forests (Cramb et al. 2004, Van Minh et al. 2020, Nguyen et al. 2025).

The forest vegetation in the Central Highlands and Southeast region is highly diverse and comprises various forest types, such as tropical evergreen closed forests, deciduous dipterocarp forests, mixed broadleaf and coniferous forests, and coastal mangrove forests (Lung et al. 2011, Luong et al. 2015). These natural forest ecosystems play a vital role in biodiversity conservation, water resource regulation, and watershed protection. However, the area of natural forests is decreasing due to logging activities, land use conversion, and agricultural expansion.

The Central Highlands and Southeast regions of Vietnam play a crucial ecological and economic role, providing important water resources, biodiversity, special-use forests, and protective forests. They also have distinct topographic and soil characteristics that make monitoring mountainous forests and industrial plantations challenging, particularly due to elevation changes and basalt soils. Additionally, this region is under significant pressure from land-use changes, including the expansion of industrial crops, agriculture, urbanization, and logging. As a result, there is a need for a regional-scale assessment of land cover changes to support effective management and policy-making.



Fig. 1. Locations of the Central Highlands and Southeast Region, Vietnam

Data

Remote sensing data

This study utilized Sentinel-2 MultiSpectral Instrument (MSI) data acquired from the European Space Agency (ESA) to classify forest vegetation and assess changes within the Central Highlands and Southeast regions of Vietnam, covering the period from 2016–2024 (Table 1).

Sentinel-2 MSI (Level-2A surface reflectance) data were selected for their 10–20 m spatial resolution and the availability of Red Edge and SWIR bands, which improve discrimination of diverse tropical forest types across complex terrain. We used cloud-reduced dry-season composites for four target years (2016, 2020, 2021, and 2024). These years were chosen to align with national forest inventory cycles and reporting milestones to maximize policy relevance. In addition, high-quality Sentinel-2 L2A products with low cloud cover were available for the study area (Table 1). The timeline includes an initial baseline (2016), an intermediate phase covering pre- and post-policy/land-use changes (2020 and 2021), and the most recent map (2024) to capture short- and medium-term dynamics. Using dry-season composites (specifically images from around July for consistency) reduces phenological variability and improves interannual comparability.

Images were selected on the basis of minimal cloud cover and optimal image quality for each target year, including 2016, 2020, 2021 and 2024. These selection processes were performed via the Google Earth Engine (GEE) cloud computing platform, which enables efficient access and processing of a large volume of Sentinel-2 data.

The Sentinel-2 image data were preprocessed via the following steps:

- Atmospheric Correction: The Sen2Cor algorithm within the Sentinel application platform (SNAP) was used to mitigate atmospheric effects (absorption and scattering) and convert top-of-atmosphere reflectance values to surface reflectance values, increasing the accuracy of subsequent classification procedures.

- Spatial Subset (Clipping): Sentinel-2 images were spatially clipped to the boundaries of the study area to minimize data storage requirements and processing times.

- Vegetation Index Calculation: Standardized vegetation indices, including the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI), were calculated from Sentinel-2 spectral bands. The formulations for the NDVI and EVI calculations are as Eq. (1) (Rouse et al. 1974, Tucker 1979):

$$EVI = 2.5 \times \frac{R_{nir} - R_r}{R_{nir} + C1 \times R_r - C2 \times R_b + L} \quad (1)$$

Table 1. Sentinel-2 satellite image parameters at the time of image collection

Year	Collection ID	Compositing Period	Platform	Cloud cover (%)	Season	Cloud-mask method	Bands
2016	COPERNICUS/S2_SR (L2A)	Dry Season Composite and July 2016	S2A	<10	Dry Season	QA60 bitmask	B2;B3;B4;B5;B6;B7;B8; B8A;B11;B12
2020	COPERNICUS/S2_SR (L2A)	Dry Season Composite and July 2020	S2B	<5	Dry Season	SCL cloud/shadow mask	B2;B3;B4;B5;B6;B7;B8; B8A;B11;B12
2021	COPERNICUS/S2_SR (L2A)	Dry Season Composite and July 2021	S2B	<5	Dry Season	SCL cloud/shadow mask	B2;B3;B4;B5;B6;B7;B8; B8A;B11;B12
2024	COPERNICUS/S2_SR (L2A)	Dry Season Composite and July 2024	S2B	<2	Dry Season	QA60 + SCL + BRDF mask	B2;B3;B4;B5;B6;B7;B8; B8A;B11;B12

Bands 5, 6, 7, 8A, 11, and 12 are 20 m; Bands 1, 9, and 10 are 60 m.

Where R_b , R_r , and R_{nir} refer to the spectral reflectance values in the blue, red, and near-infrared bands, respectively.

$C1$ and $C2$ are atmospheric correction coefficients (typically 6 and 7.5, respectively) designed to account for aerosol scattering in the red and blue bands, minimizing atmospheric influence and improving the linearity of the EVI signal.

L is a canopy background adjustment factor (typically 1) used to decouple soil background reflectance from the vegetation signal, particularly in areas with sparse canopy or varying soil conditions.

For Sentinel-2 images, the coefficients $C1$, $C2$, and L are set to the widely adopted standard values of 6, 7.5, and 1, respectively, as recommended for optimal EVI performance across various sensors (Huete et al. 2011).

Methods

Vegetation classification

Leveraging Sentinel-2 imagery and ancillary datasets, this study utilized the robust and effective RF algorithm, a supervised machine learning technique, for forest type classification (Breiman 2001). The overall classification process involved careful feature selection, systematic training sample collection, robust model training and optimization, and thorough accuracy assessment as detailed below.

Feature selection

The input feature set included spectral bands from Sentinel-2 images (B2, B3, B4, B8, B11, and B12), vegetation indices (NDVI and EVI), and terrain variables (slope, slope direction, and elevation). The selection of these features was based on their theoretical capacity to distinguish different types of vegetation in the study area, as well as insights gained from prior studies.

Training sample collection

Training samples were collected to represent the main vegetation types in the study area, such as tropical evergreen closed forests, deciduous open forests, plantations, and bare land (Fig. 2). The sources for sample collection included field surveys, high-resolution satellite imagery, and expert knowledge. A total of 12,000 reference samples were meticulously digitized. These samples were then proportionally allocated to individual classes based on their prevalence and distinctiveness. For example, Rich primary evergreen broadleaved forest (TXG1) had 209 samples, while croplands (NN) had 61 samples in 2024.

These samples were spatially distributed across the study area to ensure representativeness of various conditions and vegetation heterogeneity, as visually depicted in Fig. 2. From this total, 2100 samples (70%) were randomly selected for model training, and the remaining 900 samples (30%) were reserved as an independent test set for accuracy assessment (Table 2).

Random forest model training and classification

The RF model was trained using the 70% training data, implemented using the scikit-learn library in Python. To optimize the Random Forest model for robust vegetation classification, a systematic hyperparameter tuning process

was conducted. Key hyperparameters, *n_estimators* (number of trees) and *max_features* (number of features considered at each split), were thoroughly evaluated. A range of values was tested: *n_estimators* (100, 200, 500, 1000) and *max_features* (from 1 to 10 with a step size of 1). Initial tests indicated that model stability and performance convergence primarily occurred when *n_estimators* ranged from 400 to 500. Consequently, *n_estimators* = 500 was chosen as the optimal value, balancing computational efficiency with predictive accuracy.

For *max_features*, testing across the specified range revealed that values of 2, 3, or 4 consistently yielded the highest classification performance. Detailed evaluation using the validation set showed that *max_features* = 3

Table 2. Number of sample points over time

№	Symbol	Types of forests	2016		2020		2021		2024	
			T	R	T	R	T	R	T	R
1	TXG1	Rich primary evergreen broadleaved forest	173	74	157	67	149	64	146	63
2	TXB1	Medium primary evergreen broadleaved forest	179	77	189	81	169	72	179	75
3	TXG	Rich secondary evergreen broadleaved forest	101	43	168	72	165	71	167	72
4	TXB	Medium secondary evergreen broadleaved forest	167	72	154	66	147	63	146	63
5	TXN	Poor secondary evergreen broadleaved forest	140	60	384	165	214	92	136	58
6	TXK	Very poor secondary evergreen broadleaved forest	155	66	79	34	118	51	102	44
7	TXP	Rehabilitation secondary evergreen broadleaved forest	140	60	141	60	55	24	85	36
8	RLG	Secondary deciduous forest	67	29	50	21	129	55	126	54
9	TXDG	Rich secondary coniferous forest	69	30	92	39	42	18	37	16
10	LKB	Medium secondary coniferous forest	70	30	160	69	66	28	67	29
11	RND	Secondary evergreen broadleaved forest on rocky mountain	118	51	66	28	106	45	304	130
12	RKG	Mixed wood-coniferous forest	55	24	64	27	150	64	126	54
13	RNMG	Mangrove forest	81	35	16	7	95	41	60	26
14	TLU	Bamboo forest	164	70	5	2	43	18	34	15
15	HG1	Mixed wood-bamboo forest	93	40	141	60	154	66	30	13
16	CDD	Palm and coconut tree forest	99	42	89	38	82	35	153	66
17	RTG	Timber plantation	55	24	38	16	54	24	75	32
18	DT2	Grasslands, shrubs, regenerated trees	45	19	31	15	45	19	39	17
19	NN	Crop lands	54	23	32	14	52	22	43	18
20	MN	Water bodies	34	15	20	9	33	14	22	9
21	DK	Other lands	41	16	24	10	32	14	23	10
Total			2100	900	2100	900	2100	900	2100	900
Overall accuracy			88.55		90.02		89.63		90.53	

Note: T = Training samples; R = Remaining samples.

achieved the highest overall accuracy (OA) of 90.53%, outperforming $\text{max_features} = 2$ (OA = 89.2%) and $\text{max_features} = 4$ (OA = 88.8%). Therefore, the final Random Forest classifier was configured with $\text{n_estimators} = 500$, $\text{max_features} = 3$, $\text{max_depth} = \text{None}$, $\text{min_samples_leaf} = 1$, and $\text{random_state} = 42$. After training, the optimized RF model was applied to the Sentinel-2 imagery for each target year (2016, 2020, 2021, 2024) to generate classified vegetation maps.

To assess forest change, vegetation classification maps from 2016, 2020, 2021, and 2024 were compared using a "pixel-based change detection" approach within ArcGIS, identifying deforestation, reforestation, and vegetation type conversion. The selection of these specific years (2016, 2020, 2021, and 2024) was primarily driven by their alignment with national forest inventory cycles and mandated project reporting milestones, ensuring the direct relevance and applicability of our findings for national forest management and policy.

Accuracy assessment

The accuracy of the land cover classification was assessed via precision, recall, and F1-scores for each class (Liang 2022). The F1 score provides a key metric for evaluating classification model performance, particularly

in datasets with imbalanced class distributions. It reflects the harmonic mean of precision and recall, providing a comprehensive measure of the model's ability to both minimize false positives and correctly identify pixels belonging to each land cover class.

Precision, which represents the proportion of pixels correctly classified into a specific class out of all the pixels predicted to belong to that class, was calculated as Eq. (2):

$$\text{Precision} = \frac{TP}{TP + FP} \quad (2)$$

where true positive (TP) denotes the number of samples correctly classified as belonging to their respective class; false positive (FP) represents the number of samples incorrectly classified as belonging to a given class; and false negative (FN) indicates the number of samples that belong to a given class but are misclassified as belonging to another class.

Recall, also known as sensitivity, quantifies the model's ability to correctly identify all pixels belonging to a particular class and is defined as Eq. (3):

$$\text{Recall} = \frac{TP}{TP + FN} \quad (3)$$

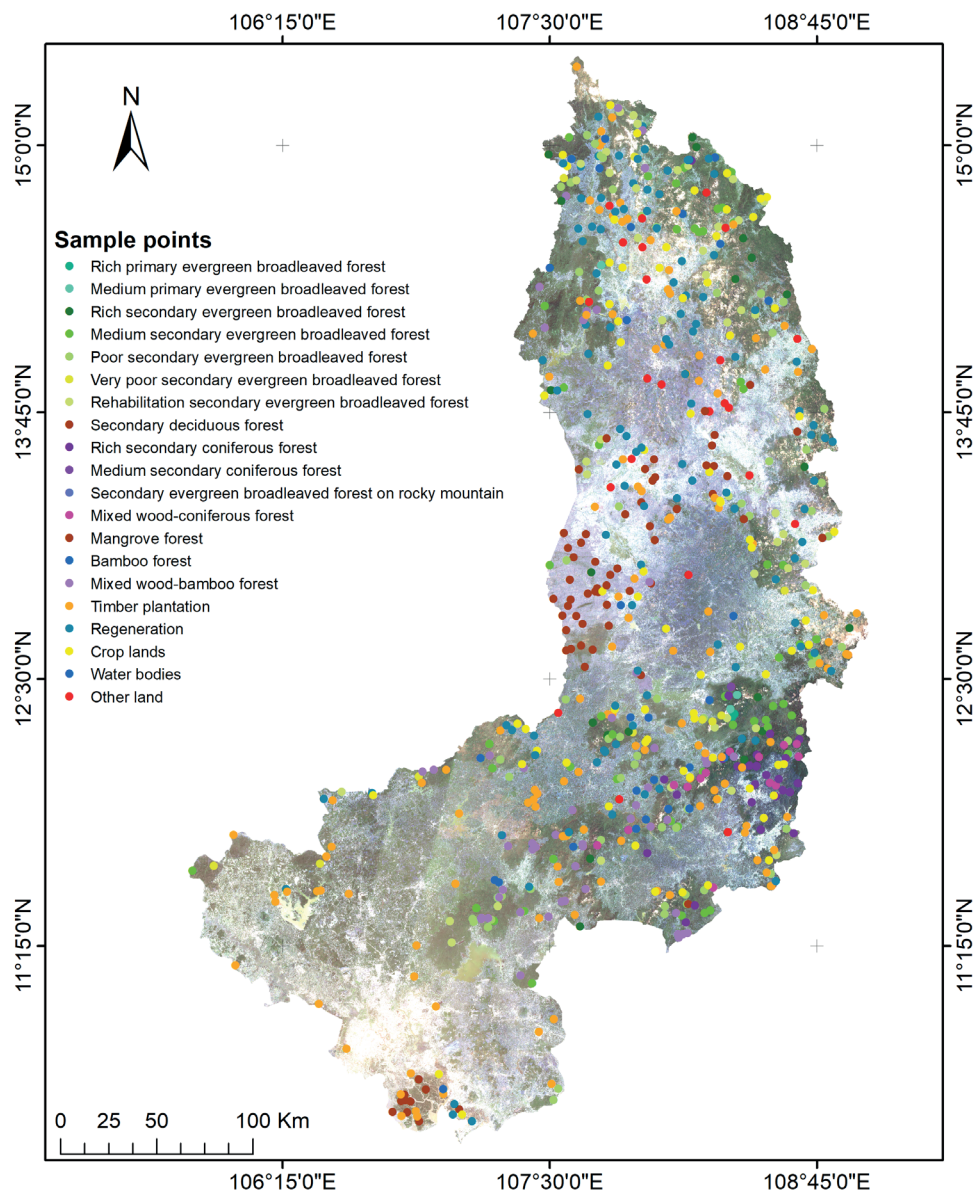


Fig. 2. Classification samples in the study area

The F1 score, which balances precision and recall, was computed via the following Eq. (4):

$$F1\ score = 2 \frac{precision \times recall}{precision + recall} \quad (4)$$

This metric ensures that a high F1 score is achieved only when both precision and recall are high, providing a more robust assessment of classification performance. The F1 score ranges from 0 to 1, with a value of 1 representing perfect classification accuracy.

Vegetation Change Assessment

To assess the changes in forest vegetation from 2016 to 2024, we employed a pixel-based post-classification comparison method. This approach involves the sequential comparison of independently generated vegetation classification maps for each target year (2016, 2020, 2021, and 2024). Specifically, we overlaid pairs of classification maps representing consecutive periods, such as 2016–2020, 2020–2021, and 2021–2024, using ArcGIS software. By analyzing the transition matrix generated from these overlays, we identified three primary types of vegetation change:

Deforestation: This refers to the conversion of any type of “forest” (e.g., tropical evergreen closed forest, deciduous dipterocarp forest, timber plantations) to any type of “non-forest” (e.g., agricultural land, bare land, built-up areas, water bodies).

Forest restoration: This is the transition from any type of “non-forest” to any type of “forest.”

Vegetation type transition: This describes the change between different types of “forest” (e.g., from tropical evergreen closed forest to deciduous dipterocarp forest) or between different types of “non-forest.”

Pixels that maintained their original classification throughout the study period were categorized as “unchanged.” This comprehensive method enables us to quantify the total area change and identify specific land use transitions and their geographical locations, offering detailed insights into the drivers and impacts of vegetation dynamics.

RESULTS

Forest types

In this study, the vegetation and land cover classification process identified 21 distinct classes across Vietnam's Central Highlands and Southeast regions. These classes were selected based on their structural, compositional, ecological roles, and management objectives, allowing for a comprehensive assessment of the diverse vegetation within the area. The main classified and compared classes include the following:

Natural forest types: This category encompasses various forms of evergreen broadleaf forests (e.g., Rich primary evergreen broadleaf forest – TXG1, Medium secondary evergreen broadleaf forest – TXB, Poor secondary evergreen broadleaf forest – TXN, etc.), secondary coniferous forests (TXDG, LKB), secondary deciduous forests (RLG), mixed wood-coniferous forests (RKG), mixed wood-bamboo forests (HG1), mangrove forests (RNMG), and bamboo forests (TLU).

Plantation forest types: this category primarily includes timber plantations (RTG) and palm/coconut tree forests (CDD).

Other vegetation and non-forest land: this group covers grasslands, shrubs, regenerated trees (DT2), crop lands (NN), water bodies (MN), and other land (DK).

A complete list of these classes and their corresponding symbols are detailed in Table 2 and the legend of Fig. 2.

Classification accuracy

The accuracy of the vegetation classification map was evaluated using the precision, recall, and F1 score metrics detailed in the methods section (Eqs. 2–4). Table 3 presents the accuracy assessment results for the 2024 classification map, offering a comprehensive overview of the classification performance.

The accuracy assessment revealed that forest types with distinct spectral characteristics were classified with high accuracy. For example, mangrove forest, timber plantation, and deciduous broadleaf forest showed elevated F1 score values (0.93, 0.90, and 0.87, respectively), demonstrating the model's ability to effectively discriminate these land cover types on the basis of their unique spectral signatures. In contrast, lower accuracy was observed for more complex forest types or those exhibiting spectral overlap with other land use categories. Rich evergreen broadleaf forest and palm forest, for example, yielded lower F1 score values (0.55 and 0.56, respectively), indicating challenges in distinguishing these classes owing to the inherent variability in forest structure, spectral confusion, or potentially nonrepresentative training samples.

Furthermore, an imbalance between precision and recall was observed for certain forest types, with rich evergreen broadleaf forests exhibiting low recall (0.46) and relatively high precision (0.70). This suggests that while the model demonstrates high confidence when classifying pixels as Rich evergreen broadleaf forests, it tends to omit pixels belonging to this class. These results indicate that the random forest algorithm generally performed well in classifying forest vegetation within the study area, but further refinements are needed to improve accuracy for complex forest types or those with significant spectral overlap with other land use categories.

The comparison of classification performance across different categories shows that classes with distinct spectral signatures and enough reference samples, such as mangrove forests, plantations, and secondary deciduous forests, were classified more accurately. In contrast, classes that exhibited high structural variability or spectral confusion, like several semi-natural evergreen broadleaf types and palm/coconut stands, were classified less reliably. The model appeared to be conservative for some high-value classes, particularly TXG, which resulted in high precision but low recall. This suggests that many true pixels were not classified—likely due to within-class heterogeneity or insufficient training samples that represent these classes adequately. Key sources of confusion include classes with similar structures or those located in transitional zones (which lead to mixed pixels), as well as areas with complex topography that create issues with illumination and shadow effects.

These observations highlight two main avenues for improvement: (1) targeted augmentation of training samples for underperforming classes, which should include additional field observations and high-resolution image analysis in boundary areas, and (2) the incorporation of complementary data, such as LiDAR, multi-temporal Sentinel-2 time series, or other spectral indices, to improve the discrimination among spectrally similar classes.

Table 3. Accuracy assessment results for the Central Highlands and Southeast Region

Nº	Symbol	Types of forests	Precision	Recall	F1 Score
1	TXG1	Rich primary evergreen broadleaved forest	0.74	0.65	0.69
2	TXB1	Medium primary evergreen broadleaved forest	0.85	0.82	0.84
3	TXG	Rich secondary evergreen broadleaved forest	0.70	0.46	0.55
4	TXB	Medium secondary evergreen broadleaved forest	0.86	0.89	0.88
5	TXN	Poor secondary evergreen broadleaved forest	0.76	0.73	0.74
6	TXK	Very poor secondary evergreen broadleaved forest	0.75	0.71	0.73
7	TXP	Rehabilitation secondary evergreen broadleaved forest	0.87	0.89	0.88
8	RLG	Secondary deciduous forest	0.88	0.86	0.89
9	TXDG	Rich secondary coniferous forest	0.74	0.69	0.72
10	LKB	Medium secondary coniferous forest	0.81	0.78	0.80
11	RND	Secondary evergreen broadleaved forest on rocky mountain	0.87	0.84	0.85
12	RKG	Mixed wood-coniferous forest	0.74	0.76	0.75
13	RNMG	Mangrove forest	0.91	0.90	0.93
14	TLU	Bamboo forest	0.88	0.89	0.86
15	HG1	Mixed wood-bamboo forest	0.82	0.84	0.83
16	CDD	Palm and coconut tree forest	0.62	0.51	0.56
17	RTG	Timber plantation	0.88	0.92	0.9
18	DT2	Grasslands, shrubs, regenerated trees	0.73	0.67	0.7
19	NN	Crop lands	0.85	0.82	0.84
20	MN	Water bodies	0.82	0.77	0.79
21	DK	Other lands	0.87	0.89	0.88
Average			0.81	0.78	0.79

Spectral characteristics of vegetation classes

On the basis of the accuracy assessment results, the reflectance spectral characteristics of different land cover types within the Central Highlands and Southeast regions of Vietnam were analyzed (Figs. 3–5).

Compared with non-forested land cover (e.g., other land and agriculture), natural forest types (e.g., rocky montane forest and evergreen broadleaf forest) generally presented lower reflectance values in the blue (0.17–0.20), green (0.17–0.20), and red (0.14–0.18) spectral regions. This pattern reflects the strong absorption of incident radiation by chlorophyll and other photosynthetic pigments within the plant canopies (Zhang et al. 2023). In contrast, the near-infrared (NIR) spectral region, which is highly sensitive to differences in vegetation structure and the internal structure of the leaf, presented relatively high reflectance values for forest types (0.30–0.45), indicating healthy leaf cellular structure and high water content (Fig. 3).

The vegetation red edge (VRE) channels (VRE1, VRE2, VRE3, and VRE4), which are sensitive to subtle variations in leaf cellular structure and chlorophyll content, also exhibited significant differences among vegetation types (Fig. 4). The forest types characterized by dense canopies (e.g., evergreen broadleaf forest and mixed forest) generally presented relatively high reflectance values in the VRE channels, which was indicative of relatively high aboveground biomass and chlorophyll concentrations. Conversely, non-forested land cover types (e.g., other land, agriculture) presented lower reflectance values in these spectral regions.

Shortwave infrared (SWIR) channels (SWIR1 and SWIR2), which are sensitive to variations in foliar and soil moisture contents, likewise provide differentiation among vegetation types (Fig. 5). Denser forest canopies are generally characterized by lower reflectance values in the SWIR channels, reflecting higher LWC. In contrast, non-forested land cover types presented higher reflectance values in these regions.

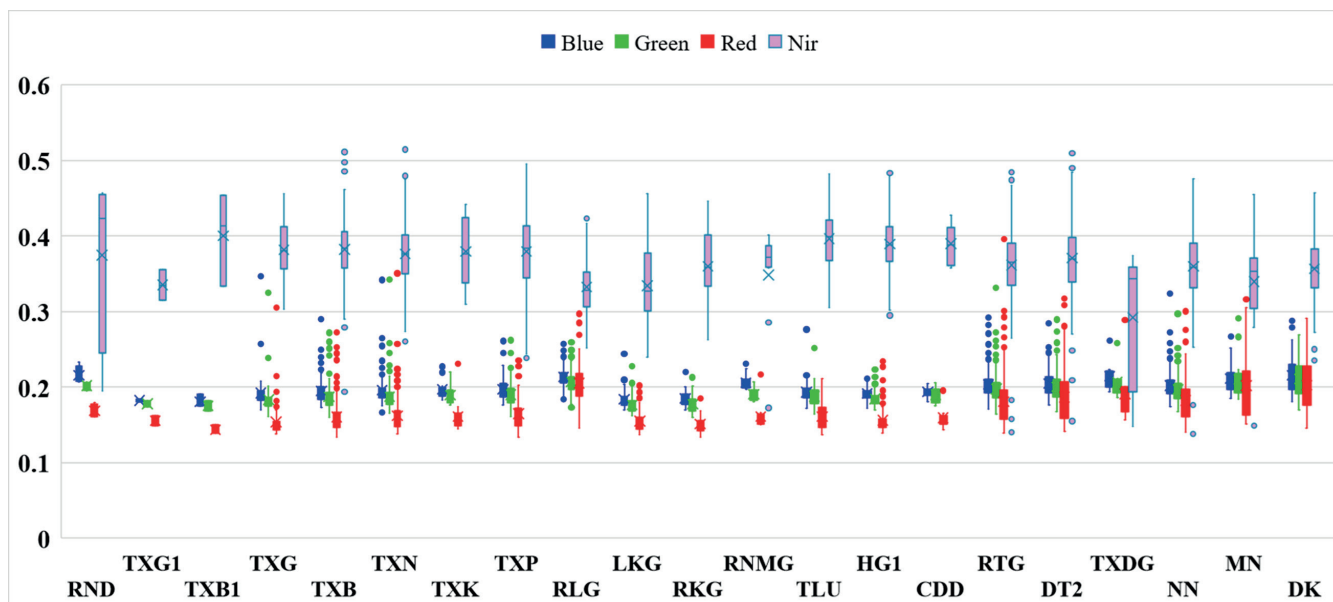


Fig. 3. Reflective spectral values of land cover types for four channels: blue, green, red, and NIR

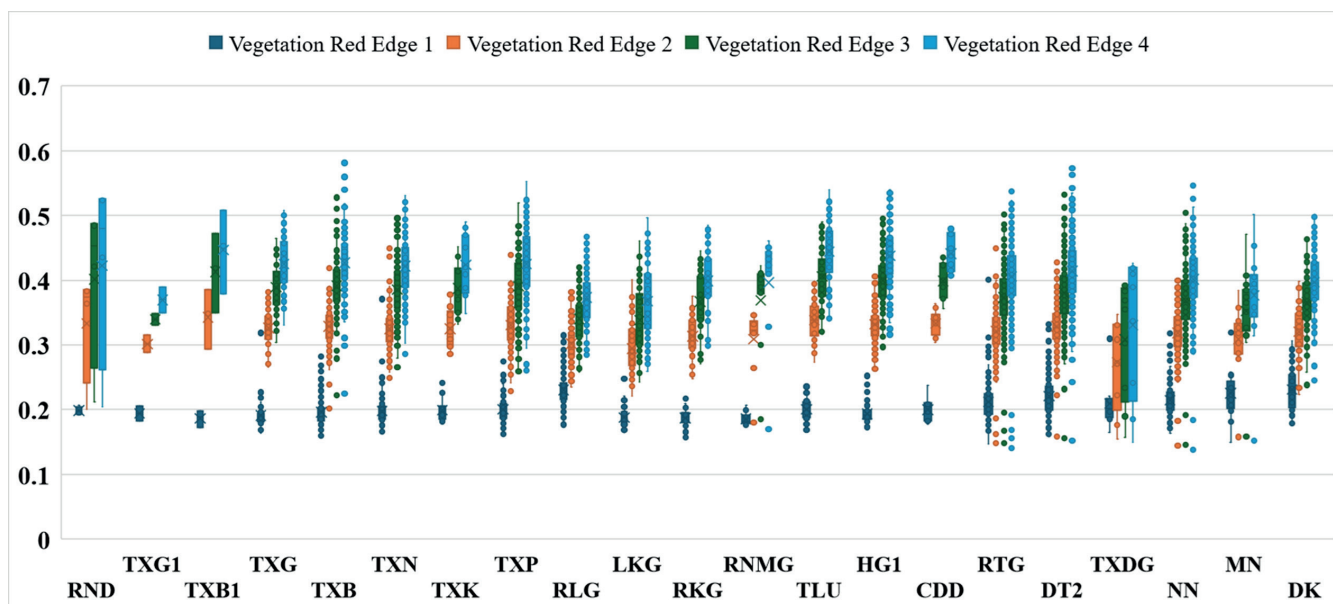


Fig. 4. Reflection spectral values of the overlay types for the four vegetation red edge spectral channels 1, 2, 3, and 4

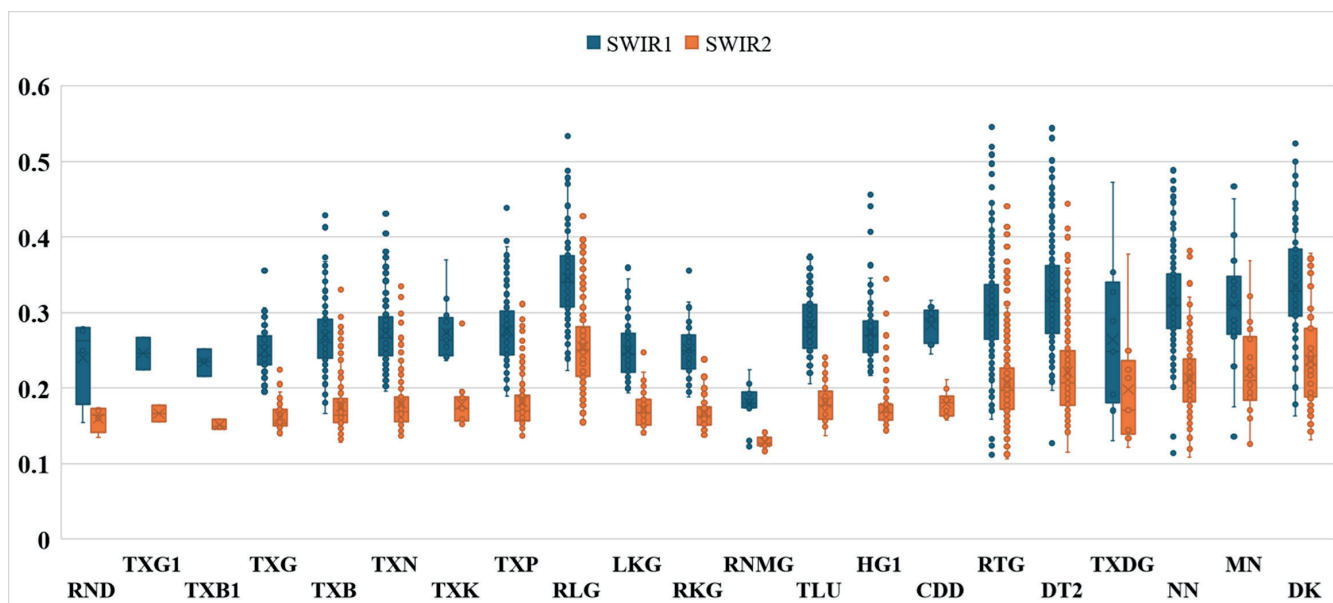


Fig. 5. Reflection spectral values of overlay types for 2 spectral channels, SWIR1 and SWIR2

Vegetation area and change

On the basis of the accuracy assessment, a map illustrating the current vegetation cover status for the Central Highlands and Southeast regions was created for 2016, 2020, 2021, and 2024 (Fig. 6). Table 4 presents the areas of the main vegetation types in the study area for these years.

According to the 2024 data (Table 4), the Central Highlands and Southeast regions maintain a diverse array of vegetation types, although some area changes have occurred since 2016.

Evergreen broadleaf forests represent the largest proportion, covering 665,792.3 hectares. These forests are predominantly situated within special-use forests (including national parks and nature reserves) and watershed protection areas, underscoring their significant ecological role in the region. Spatially, these evergreen broadleaf forests are primarily distributed across the eastern and northeastern parts of Gia Lai and Kon Tum

provinces, extending into the southwestern section of Kon Tum province, the eastern areas of Dak Lak and Dak Nong provinces, and the northern reaches of Lam Dong province.

Timber plantations (RTG) also play an essential economic role, occupying 644,649.7 hectares. This forest type is widely distributed throughout the study area, stretching from the northern parts of Kon Tum province down to the southern extent in Ho Chi Minh City. Notably, the dominant species in timber plantations vary geographically: *Acacia mangium* is prevalent in the Central Highlands, whereas rubber (*Hevea brasiliensis*) plantations are more common in the Southeast region. Other natural forest types occupy smaller areas; for instance, poor evergreen broadleaf forests (TXN) cover 276,506.8 hectares. Deciduous broadleaf forests (RLG), a characteristic forest type of the Central Highlands, span 377,617.2 hectares and are primarily located in the western parts of Gia Lai and Dak Lak provinces.

Table 4. Current area of plant cover in the Central Highlands and Southeast region from 2016–2024

№	Symbol	Types of forests	Area (ha)			
			2016	2020	2021	2024
1	TXG1	Rich primary evergreen broadleaved forest	27,006	27,006	27,006	27,006
2	TXB1	Medium primary evergreen broadleaved forest	10,236	10,236	10,236	10,236
3	TXG	Rich secondary evergreen broadleaved forest	236,944	235,067	234,958	234,777
4	TXB	Medium secondary evergreen broadleaved forest	665,799	666,878	666,765	665,792
5	TXN	Poor secondary evergreen broadleaved forest	271,930	272,726	274,318	276,507
6	TXK	Very poor secondary evergreen broadleaved forest	18,771	18,172	17,539	17,330
7	TXP	Rehabilitation secondary evergreen broadleaved forest	300,209	297,005	296,869	299,504
8	RLG	Secondary deciduous forest	376,486	378,114	377,997	377,617
9	TXDG	Rich secondary coniferous forest	1,573	1,617	1,617	1,492
10	LKB	Medium secondary coniferous forest	116,299	117,388	117,292	115,611
11	RND	Secondary evergreen broadleaved forest on rocky mountain	5,797	7,875	7,875	7,813
12	RKG	Mixed wood-coniferous forest	49,963	50,164	50,070	48,858
13	RNMG	Mangrove forest	14,426	14,608	14,552	14,333
14	TLU	Bamboo forest	58,390	59,097	58,133	59,519
15	HG1	Mixed wood-bamboo forest	273,405	275,611	276,575	275,189
16	CDD	Palm and coconut tree forest	32	32	32	32
17	RTG	Timber plantation	644,330	646,664	646,301	644,650
18	DT2	Grasslands, shrubs, regenerated trees	340,816	330,958	330,547	329,524
19	NN	Crop lands	886,286	885,374	883,922	882,730
20	MN	Water bodies	45,025	44,844	44,900	45,119
21	DK	Other lands	3,442,932	3,447,222	3,449,153	3,452,664

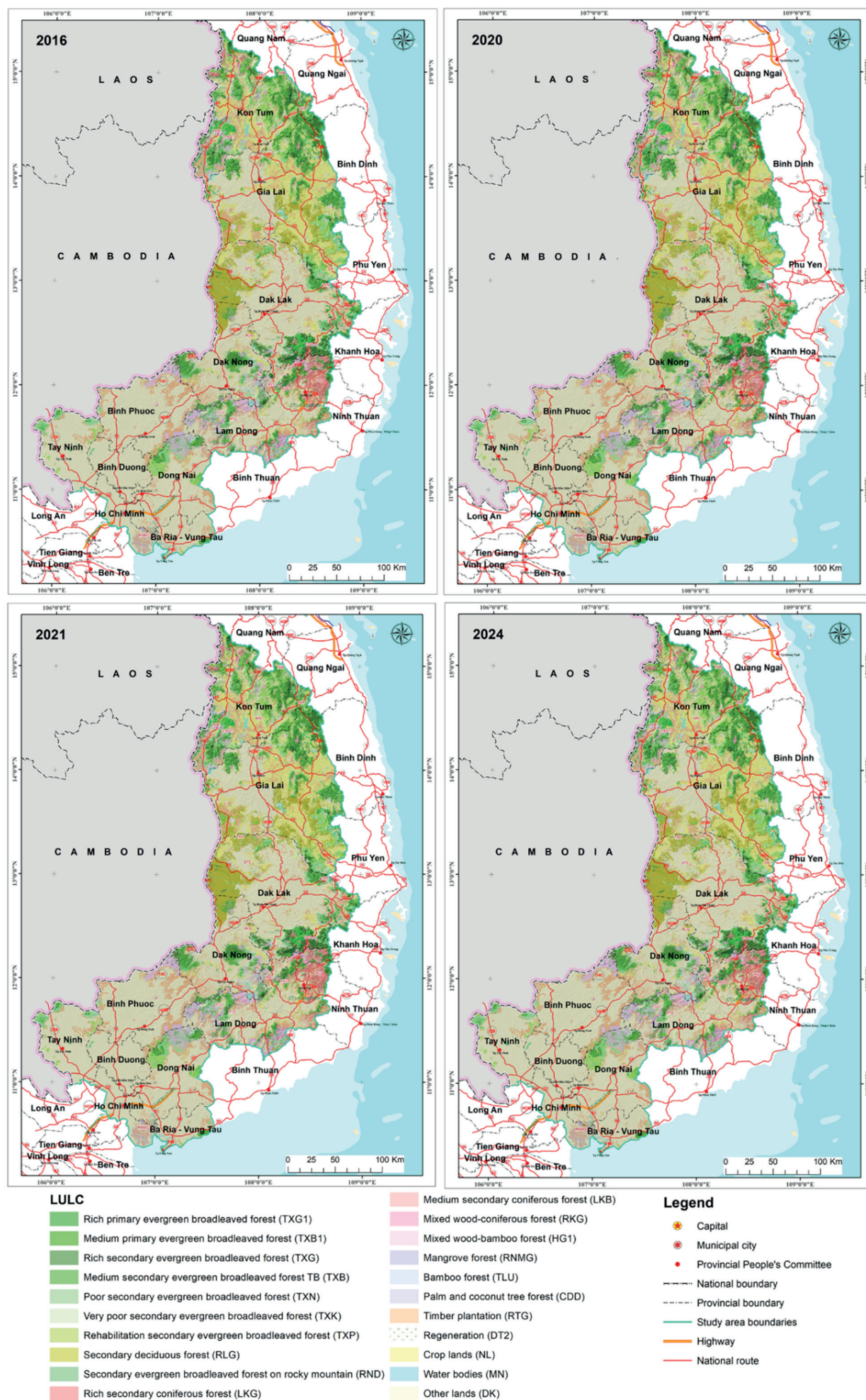


Fig. 6. Map of plant cover by period in the study area

Analysis of changes in the area of vegetation types from 2016–2024 revealed complex dynamics (Table 5). Certain vegetation types exhibit stability; for example, medium primary evergreen broadleaved forest maintained a consistent area of approximately 10,236 hectares throughout the study period, and palm and coconut tree forest remained stable at 32.2 hectares. This suggests the effectiveness of current conservation measures for these specific vegetation types.

However, area declines were noted for several natural forest types. The rich evergreen broadleaf forest area decreased from 236,943.6 hectares in 2016 to 234,777.1 hectares in 2024, a net reduction of 2,166.5 hectares. Declines are primarily located in the special-use forests and protective forests of the northern Central Highlands, including Chu Mom Ray, Kon Ka Kinh, Kon Chu Rang, and Thach Nham. The medium evergreen broadleaf forest area also experienced a slight decrease, from 665,799.2 hectares in 2016 to 665,792.3 hectares in 2024, representing a

negligible reduction of 6.9 hectares. The areas of decline are similar to those of rich evergreen broadleaf forest. The area of poor evergreen broadleaf forest reportedly increased from 271,930.0 hectares in 2016 to 276,506.8 hectares in 2024. This shift was mainly due to the area of cropland, grassland, and shrubland in the study area. Overall, Rehabilitation Evergreen Broadleaf Forests showed some signs of recovery, decreasing from only 300,208.5 hectares in 2016 to 299,504.4 hectares in 2024. These declines indicate significant pressure on natural forests due to logging activities, land-use conversion, and other factors, including climate change and forest fires.

The area designated for timber plantation (RTG) initially increased from 644,329.9 hectares in 2016 to 646,663.9 hectares in 2020 but then slightly decreased to 644,649.7 hectares by 2024. This fluctuation may be attributed to the cyclical logging of plantations or their conversion to other land uses following harvest. Another noteworthy trend is the continuous increase in the area of other lands

Table 5. Transformation of plant cover areas in the Central Highlands and Southeast Vietnam from 2016–2024

№	Sym- bol	Types of forests	Area (increase (+)/decrease (-) (ha)		
			2020-2016	2021-2020	2024-2020
1	TXG1	Rich primary evergreen broadleaved forest	0.0	0.0	0.0
2	TXB1	Medium primary evergreen broadleaved forest	0.0	0.0	0.0
3	TXG	Rich secondary evergreen broadleaved forest	-1,877.1	-108.2	-181.2
4	TXB	Medium secondary evergreen broadleaved forest	1,078.6	-112.7	-972.8
5	TXN	Poor secondary evergreen broadleaved forest	796.2	1,592.0	2,188.6
6	TXK	Very poor secondary evergreen broadleaved forest	-600.2	-633.1	-209.0
7	TXP	Rehabilitation secondary evergreen broadleaved forest	-3,203.2	-136.1	2,635.1
9	RLG	Secondary deciduous forest	1,628.1	-116.5	-380.1
8	TXDG	Rich secondary coniferous forest	43.5	0.0	-124.8
10	LKB	Medium secondary coniferous forest	1,088.8	-96.1	-1,680.8
12	RND	Secondary evergreen broadleaved forest on rocky mountain	2,078.2	0.0	-62.0
11	RKG	Mixed wood-coniferous forest	201.0	-94.4	-1,211.4
13	RNMG	Mangrove forest	181.8	-56.1	-219.3
14	TLU	Bamboo forest	706.7	-964.0	1,385.8
15	HG1	Mixed wood-bamboo forest	2,206.0	964.0	-1,385.8
16	CDD	Palm and coconut tree forest	0.0	0.0	0.0
17	RTG	Timber plantation	2,334.1	-363.2	-1,651.0
18	DT2	Grasslands, shrubs, regenerated trees	-9,858.0	-411.4	-1,023.1
19	NN	Crop lands	-912.8	-1,451.4	-1,192.3
20	MN	Water bodies	-181.8	56.1	219.3
21	DK	Other lands	4,290.3	1,931.2	3,511.1

during the study period, which expanded from 3,442,931.9 hectares in 2016 to 3,452,664.4 hectares in 2024. This reflects the ongoing conversion of forestland to various other uses, including agricultural and construction land, which can have detrimental impacts on biodiversity, the ecological functions of forests, and the provision of ecosystem services.

Within the study area, forests within national parks and nature reserves exhibit relatively small fluctuations, partly due to the stable forest structure and effective management and protection efforts by local units. In contrast, the land cover types with the greatest area changes, such as grasslands, shrubs, and regenerated trees, are predominantly found in the buffer zones surrounding these national parks and nature reserves. The changes in various types of vegetation, particularly the decline in natural forest areas and the increase in non-forest land, highlight a complex interplay of ecological, socioeconomic, and policy factors. Certain forest types, such as evergreen broadleaf forests, appear more vulnerable to degradation, likely due to their structural weaknesses and direct human impacts. The rapid growth of “other lands” and “crop lands” indicates significant pressure on forest ecosystems.

Socioeconomic factors, including rising population density, the demand for agricultural land, and infrastructure development, directly influence these land-use changes. Economic incentives for converting forest land to agriculture or other uses often outweigh the benefits of preserving forest cover, particularly for local communities seeking to improve their livelihoods.

Policy frameworks also play a crucial role in shaping these dynamics. While forest protection and reforestation policies have led to some recovery—especially in planted forests—the continued decline in natural forests reveals gaps or challenges in policy implementation. The differing rates of decline observed between the 2016–2020 and 2021–2024 periods for natural forests suggest that recent policy adjustments or improved enforcement may be producing initial positive outcomes; however, further investigation is necessary. This situation underscores the need for adaptive management strategies that address both the direct and indirect drivers of deforestation and forest degradation, taking into account the specific ecological and socioeconomic contexts of different forest types.

DISCUSSION

Forest vegetation plays a critical role in maintaining ecological stability, conserving biodiversity, and providing essential ecosystem services (Brockerhoff et al. 2017, Wani et al. 2021). The Central Highlands and Southeast regions of Vietnam are home to diverse and ecologically significant forest ecosystems that contribute substantially to regional socioeconomic development and environmental protection (Cramb et al. 2004, Salemink 2018). This study provides a comprehensive assessment of the status and dynamics of forest vegetation in these regions from 2016–2024. The results of our vegetation classification indicate a diverse distribution of forest types, including tropical evergreen closed forests, deciduous dipterocarp forests, timber plantations, and non-forested land cover. However, analysis revealed a notable decline in the natural forest area during the study period.

The reflectance spectral characteristics of vegetation types are essential for accurate forest classification and monitoring. Natural forest types generally exhibit lower reflectance values in the blue, green, and red spectral bands because of the strong absorption of incident radiation by

chlorophyll (do Amaral et al. 2019). Conversely, the near-infrared spectral region presents relatively high reflectance values for forest types, reflecting the leaf cellular structure and water content (Sims et al. 2002, Ullah et al. 2014). Vegetation red edge channels provide valuable information regarding vegetation health and physiological conditions (Shamsoddini et al. 2018), whereas SWIR channels are sensitive to variations in foliar and soil moisture content (Ullah et al. 2014). Integrating these spectral bands facilitates the accurate discrimination of diverse vegetation types and the monitoring of their temporal dynamics (Verrelst et al. 2019). Despite thorough preprocessing steps, which include atmospheric correction and cloud masking, remote sensing data still contains various types of noise. This noise can come from residual atmospheric effects, sensor-specific artifacts, and, notably, topographic variations in illumination, such as shadows and varying sun angles on slopes that are common in the mountainous Central Highlands. Such residual noise can significantly decrease the spectral separability between closely related vegetation types and contribute to mixed pixels. This, in turn, affects the overall accuracy and reliability of classification and change detection results. The lower F1 scores observed for certain complex forest types, such as rich evergreen broadleaf forests and coconut tree forests, may be partially due to these noise-induced spectral ambiguities, which complicate the precise delineation of class boundaries, even when using advanced machine learning algorithms.

Our change analysis reveals spatially heterogeneous losses and gains across the study area. At the class level, Rich secondary evergreen broadleaved forest experienced a net loss of 2,166.5 ha (2016–2024), while Medium secondary coniferous forest declined by 1,776.8 ha over the same period. These class-level changes are spatially concentrated: losses of high-value evergreen forests are primarily located in special-use and protection forest blocks in the northern Central Highlands (notably Chu Mom Ray, Kon Ka Kinh, Kon Chu Rang and Thach Nham). Compared with prior studies conducted in this region, our findings are consistent with reports of deforestation and forest degradation in the Central Highlands and Southeast regions (Khuc et al. 2018, Ebright et al. 2023). Prior studies have identified logging activities, land-use conversion, and agricultural expansion as the primary drivers of deforestation in this area (Meyfroidt et al. 2008, Meyfroidt et al. 2013, Tran et al. 2022). However, the present research provides more detailed quantitative evidence regarding the decline in area for specific forest types, as well as the expansion of nonforestland cover. Notably, the rate of natural forest decline slowed during the 2021–2024 period compared with the 2016–2020 period, potentially reflecting the effectiveness of conservation initiatives and/or the influence of broader climatic trends. Further research is warranted to elucidate the relative contributions of these factors. The timber plantation area showed short-term increase from 2016 to 2020 (+2,334.1 ha) followed by a modest decrease by 2024 (net +683.1 ha relative to 2016), consistent with harvest–replant cycles. The observed increase in timber plantation area from 2016–2020 indicates the initial success of afforestation programs; however, this area experienced a slight decrease from 2021–2024, likely due to timber harvesting or conversion to alternative land uses. This suggests the need for more effective and sustainable exploitation and management practices within timber plantation systems.

Both natural and anthropogenic factors influence vegetation dynamics within the study area. In addition to human impacts, natural factors such as climate (rainfall, temperature), topography (elevation, slope), and soil conditions also influence the distribution and development

of different vegetation types (Zheng 2006, Dong et al. 2014, Asefa et al. 2020). Wildfires and disease outbreaks can also lead to significant forest degradation (Cobb et al. 2016). Anthropogenic influences, including illegal and unsustainable logging, land-use conversion (particularly for agriculture and urban development), and unsustainable farming practices, are major contributors to deforestation and forest degradation (Kyere-Boateng et al. 2021, Burgess et al. 2022). Furthermore, forest management policies can exert both positive and negative influences on vegetation dynamics (McCarthy et al. 2011, Choi et al. 2021).

A significant challenge in classifying forest vegetation in the study area arises from the seasonal spectral variations observed in semi-evergreen forests, which can result in misclassification (Mamnun et al. 2020). To tackle this issue, our methodology strategically employed Sentinel-2 imagery, primarily captured during the peak of the wet season in July for the respective study years (Mai Son et al. 2025). During this time, semi-evergreen vegetation is in its most vigorous growth phase, demonstrating optimal photosynthetic activity and a maximum leaf area index. This consistent phenology provides a more distinct and stable spectral signature, making it easier to differentiate from other types of vegetation. This targeted image acquisition strategy, complemented by ground validation, was essential for improving classification accuracy for these dynamic forest types, ultimately enhancing the reliability of our vegetation maps.

The Central Highlands and Southeast regions of Vietnam have significant potential for forest restoration across various landscape types. Degraded forest patches or buffer zones adjacent to relatively intact forest cores, such as areas converted from barren land, benefit from natural restoration due to local seed sources and connections to nearby protected areas. Plantation areas often exhibit rapid recovery cycles upon replanting, making it essential to prioritize the conversion to mixed native species to enhance biodiversity. Restoration priorities should be determined using a multi-criteria index that considers factors such as distance to primary forest, conversion time, threat level, socioeconomic feasibility, and landscape connectivity potential. On a practical level, initial priority actions include protecting areas from encroachment, supporting natural regeneration in marginal forest patches, and replanting native species in severely degraded areas. Monitoring the progress of recovery can be conducted continuously using Sentinel-2 satellites to analyze the NDVI/EVI index and cover change, in combination with field surveys to assess the quality of regeneration.

Limitations

This study demonstrated that integrating Sentinel-2 imagery with RF classification is highly effective for distinguishing different forest types. The 13 spectral bands of Sentinel-2, particularly the Red Edge and SWIR bands, are crucial for capturing changes in vegetation cover, leaf structure, and mesophyll scattering, which are essential for accurate classification in complex tropical ecosystems (Sibanda et al. 2019, E. D. Chaves et al. 2020). Additionally, using multi-temporal Sentinel-2 data enables the detection of changes over the study period, providing valuable insights into the dynamic processes of the forest (Hošćilo et al. 2019, Wakulińska et al. 2020). Third, although field data were utilized for model training and internal accuracy assessment, the comprehensive validation and independent verification of the resulting classification maps and change detection analyses with external field-collected ground

truth data were not explicitly conducted. This limitation may introduce uncertainties regarding the absolute accuracy and generalizability of the findings, particularly in ecologically complex and heterogeneous landscapes.

However, the methodology of this study has certain limitations. While Sentinel-2 offers a favorable balance between spatial and temporal resolution, its pixel size of 10-20 meters for major swaths can be a limiting factor in accurately detecting small-scale deforestation events or complex forest changes, especially in highly fragmented areas (Grabska et al. 2020). Although the RF algorithm is powerful, it can sometimes struggle with spectral confusion between certain forest types, particularly those with overlapping spectral signatures or high structural variability (Chan et al. 2008).

Future research could explore integrating very high-resolution imagery or LiDAR data to capture finer spatial details (Singh et al. 2012), as well as experimenting with more advanced deep learning algorithms to potentially improve classification accuracy and address some of the spectral limitations encountered with RF in highly heterogeneous environments (Wang et al. 2021, He et al. 2023).

CONCLUSIONS

This study assessed the status and dynamics of forest vegetation in the Central Highlands and Southeast regions of Vietnam from 2016–2024. These regions are of substantial economic, social, and environmental importance to Vietnam. With the use of Sentinel-2 remote sensing data, advanced analytical techniques, and GIS tools, a detailed vegetation classification model and corresponding maps were developed to evaluate temporal changes in the areas of different forest types. The novelty of the study lies in integrating multi-year Sentinel-2 data (2016–2024) with an RF classification framework adapted for hilly terrain through the systematic design of a stratified training model and parameter optimization.

The primary findings revealed a notable decline in the area of natural forests, particularly those of high conservation value. These findings underscore the urgent need for sustainable forest management and biodiversity conservation initiatives in this region. Consequently, we recommend immediate, practical interventions, including stricter enforcement against illegal logging, expansion of community-based conservation programs, and strategic reforestation efforts focused on restoring degraded natural forest areas. This research provides timely and comprehensive information on the status and dynamics of forest vegetation while also identifying key drivers influencing these changes and assessing the effectiveness of existing forest management policies.

These findings can inform the development of more effective forest management strategies tailored to the specific socioeconomic and environmental contexts of the region. Given the growing impacts of climate change and increasing pressure on forest resources, the adoption of remote sensing and GIS technologies for systematic forest monitoring and adaptive management is crucial. Concerted action is urgently needed to protect these invaluable forest ecosystems for the benefit of current and future generations. The results provide practical recommendations on targeted protection, community-based restoration, and conversion of plantations to natural forests at hotspots and show that if current trends continue, managed plantations may recover to a modest extent while the loss of natural forests in buffer zones outside the protected area is likely to continue over the next decade. ■

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HOLOCENE COASTAL PROCESSES OF AN UPLIFTED FENNOSCANDIAN COAST: A CASE STUDY FROM THE TURIY PENINSULA (THE NORTHERN COAST OF THE WHITE SEA)

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ABSTRACT. This study examines coastal processes and resulting morphologies during the Holocene on the Turiy Peninsula (the southern part of the Kola Peninsula). The genetic classification of the modern coasts revealed both wave- and non-wave-dominated types. Similar patterns were also identified on elevated paleocoastlines. Four geomorphological levels of the Turiy Peninsula were distinguished, considering their age and environmental settings based on field observations, interpretation of satellite images, topographic data, drilling cores, radiocarbon dating, and diatom analysis. The Turiy Peninsula provides a unique setting for paleogeomorphological research due to the good preservation of coastal landforms and the diversity of geomorphological settings. This well-preserved coastal morphology is attributed to relatively high Holocene uplift rates, which caused rapid exposure of the coasts beyond the zone of active wave impact. As such, the area represents a sensitive archive of postglacial coastline response to glacioisostatic uplift in formerly glaciated shield environments. Radiocarbon dating and diatom analysis of sediments from isolated basins allowed us to estimate the regional uplift rate over the last 3.5–4 cal kyr at 5–7 mm/year. These rates are significantly higher than the uplift rates observed in adjacent areas for the same period, supporting the interpretation of block-structured tectonic movements in the region.

KEYWORDS: coastal morphodynamics, sea level changes, diatoms, radiocarbon dating, the Holocene, Kola Peninsula coast

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INTRODUCTION

Since the end of the Last Glaciation, the coasts of Fennoscandia, and the Kola Peninsula in particular, have experienced relative sea level (RSL) fall (Koshechkin 1979; Korsakova and Kolka 2017; Baranskaya et al. 2018). This was a result of rapid isostatic land uplift that followed the retreat of the Scandinavian ice sheet (Lavrova 1960; Hughes et al. 2016). This initiated coastal processes (such as coastline progradation, coastal erosion, beach-ridge formation, etc.) that gave rise to diverse morphogenetic shore types.

Sequences of transgressive and regressive events preserved in coastal morphology offer critical insights into coastline evolution. Their reconstruction relies on coastline elevation data, morphostratigraphic indicators (e.g., number of beach ridges), and sedimentological markers (Zenkovich 1962).

In the White Sea region, deglaciation took place between ~17 and 11 cal ka BP (Demidov et al. 2006; Hughes et al. 2016; Stroeve et al. 2016; Astakhov et al. 2016). Kandalaksha Bay is the area where it occurred later than in other regions of the White Sea. The precise timing of deglaciation in this area remains debated. It is currently

assumed that deglaciation was completed here between ~12.5 and 11 cal ka BP (Astakhov et al. 2016; Astafiev et al. 2012; Evzerov et al. 2007; Korsakova et al. 2023). Initial ingress of marine waters in the eastern part of Kandalaksha Bay occurred ~13.8–12.4 cal ka BP (Kolka et al. 2013, 2015, 2016; Polyakova et al. 2023). The main stages of the postglacial evolution of the White Sea are as follows: Late Glacial transgression (~13.4–11.6 cal ka BP), rapid RSL fall/regression (~11.6–9.5 cal ka BP), an Early-Middle Holocene highstand, or the Tapes transgression (~9.5–6.8 cal ka BP), and subsequent RSL fall to the present level (Korsakova 2022). The RSL highstand reached its maximum, particularly in the apex of Kandalaksha Bay (Kolka and Korsakova 2017; Korsakova 2022).

The highest dated coastlines there reach up to 100 m a.s.l. (Baranskaya et al. 2018) or 120 m a.s.l. (Korsakova 2022). For comparison, on the Zimniy Coast of the White Sea, the highest coastlines do not exceed 14–20 m a.s.l. (Shilova et al. 2019). The uplift rate generally decreases along the northwest-southeast gradient, reflecting increasing distance from the center of the Last Glacial ice sheet (Lavrova 1960; Korsakova and Kolka 2017).

Block vertical movements along faults are superimposed on the general uplift of the Baltic Shield (Baranskaya et al. 2018; Korsakova 2022; Shvarev 2022). The Turiy Peninsula represents one of these blocks (Shvarev 2022) and displays a diverse set of coastal landforms and uplift levels. Investigating this site may provide insights into the spatial heterogeneity of postglacial movements within the Baltic Shield.

As a result of differential isostatic uplift, tectonic activity, and variations in sediment supply, the configuration of the White Sea coastline, especially within Kandalaksha Bay, changed rapidly and unevenly throughout the postglacial period, reflecting spatial variability in uplift intensity and local conditions. This led to changes in coastal processes in different parts of the coast.

This study aims to reconstruct the evolutionary stages of the Turiy Peninsula coast and to identify the key geomorphological factors that led to the formation of specific coastal morphologies in the Holocene. We conducted paleogeomorphological and lithostratigraphic studies of the Turiy Peninsula coastal topography, supported by the results of radiocarbon dating and diatom analysis.

REGIONAL SETTING AND CURRENT STATE OF THE ART

The Turiy Peninsula is located in the southern part of the Kola Peninsula and protrudes into Kandalaksha Bay of the White Sea. Its geological composition is rather homogeneous. Most of the peninsula is mantled by Quaternary sediments, which occupy various altitudinal zones across the area (Astafiev et al. 2012; Kolka et al. 2013). They are represented by a discontinuous cover of glacial, glaciofluvial sediments (sand with boulders, pebbles and gravel), marine sediments of the Late Glacial transgression (clays, rarely silts, sands, sands with pebbles) and Holocene marine sediments (silts, sands, less frequently pebble and boulder-pebble deposits, silts and clays). Only the extreme south of the Turiy Peninsula consists of Caledonian rock formations (Astafiev et al. 2012).

Despite the overall geological homogeneity, coastal morphology differs markedly between the northwestern and southeastern sectors due to contrasting hydrometeorological conditions. The highest wave energy occurs during winds from the southeast and south (Terziev et al. 1991). The maximum wave height reaches 2 m within

the SE and S coasts and does not exceed 1 m on the NW coast (Arkhipkin et al. 2015). Kandalaksha Bay of the White Sea is a subarctic basin that remains ice-covered for 6–7 months annually. However, quasi-stationary ice-free zones often form due to prevailing winds from the southeast and south. This creates conditions for wave action to impact the coasts of this part of the peninsula even within the ice-covered season (Terziev et al. 1991). Additionally, the nearshore slope morphology of the peninsula coasts is not uniform (Nikiforov et al. 2012). The NW coast (within Sosnovaya Bay) has a shallow shoreface, which is largely sheltered from wave impact. Tides are the primary driver of coastal change in this area. The SE and S coasts have a steeper shoreface and a spatial position favoring intense wave action. This combination of factors shapes the present coastal dynamics of the peninsula and probably influenced them in the past.

The coastal dynamics of the Turiy Peninsula have not been previously investigated. Nevertheless, some topographic profiles provide information on the morphology of the southeastern part of the peninsula (Kolka et al. 2013). Studies on the classification of the Turiy Peninsula coasts are scarce. Existing small-scale maps of coastal types for the Kola Peninsula and the White Sea (Safianov and Solovieva 2005; Yermolov 2010) do not allow for detailed zoning of the Turiy Peninsula coasts and uplifted land areas. Furthermore, RSL and paleogeographical reconstructions are available for adjacent territories (Umba, Kuzreka, Kanozero Lake) (Evzerov et al. 2007; Kolka et al. 2013; Grekov et al. 2013a,b; Sapelko et al. 2022; Ludikova et al. 2022). This provides a basis to compare evolutionary stages between the Turiy Peninsula and adjacent areas.

MATERIAL AND METHODS

We conducted field investigations in the northwestern (southern coast of Sosnovaya Bay) and southeastern parts of the Turiy Peninsula to reconstruct the peninsula's coastal morphodynamics and RSL fluctuations during the Holocene (Fig. 1).

Applying the principles of uniformitarianism, we interpreted the uplifted terrain through comparison with contemporary coastal morphology. The geomorphological subdivision of the area follows classical concepts of coastal morphogenesis based on the morphology of beach ridges and marine terraces, following the approach of Zenkovich (1967), Kaplin et al. (1991), and Bird (2008). The presence, number, and morphology of beach ridges, together with a straight coastline planform, indicate that wave-dominated processes (depositional and erosional) control coastal evolution. An uneven coastal bench and an indented coastline outline show that non-wave processes, often tidal, dominate the system. Rock cliffs characterize structurally primary rocky shores that are almost unchanged by wave processes.

Geomorphological studies included topographic profiling, GPS logging, and detailed description of landforms at slope transitions. Photographic documentation supplemented the field observations. Relative elevation measurements with an estimated accuracy of a few centimeters were made using a *CST Berger 17-632 Hand Sight Level* with a measuring rail. Distances were measured using the *Garmin GPSMAP 62s portable navigator* (error of ± 5 m).

We used the isolation-basin method to reconstruct RSL fluctuations. Postglacial isostatic uplift forms these basins and allows us to date former coastline positions at a common elevation. Isolation basins are widely used in reconstructions of RSL changes (Donner et al. 1977; Evzerov et al. 2007;

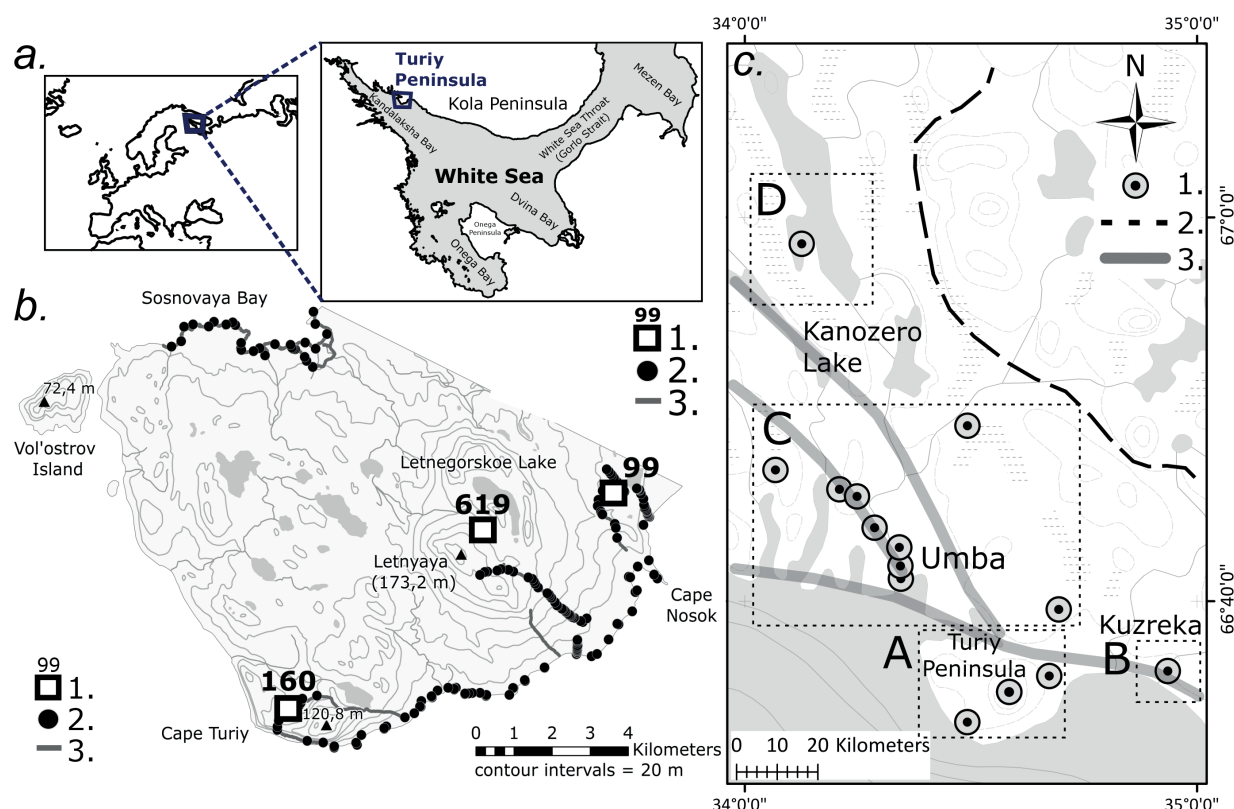


Fig. 1. Study area and current state of the art. Legend: a. Location of the study area; b. Map of the field data: 1 – positions of boreholes (boreholes are signed with numbers), 2 – points of geological and geomorphological observations, 3 – location of routes and profiles; c. The state of paleogeographic knowledge of the Turiy Peninsula and adjacent territories: A – this research, B – Grekov et al. 2013, C – Kolka et al. 2013, D – Ludikova et al. 2022; Sapelko et al. 2022; 1 – points of geological-geomorphological research, 2 – proposed boundary of the Scandinavian Ice Sheet, Salpausselkä stage I, which correlates with the Younger Dryas (Astafiev et al. 2012; Korsakova et al. 2023), 3 – elements of the fault-block structure according to (Shvarev 2022).

Subetto 2009; Baranskaya et al. 2018; Korsakova 2022). Within them, a change in sedimentation regime occurs in several stages from brackish to freshwater. Currently, some of these lakes have become freshwater, while others remain waterlogged. Establishing the time of transition from marine to freshwater conditions in these basins was among the objectives of our research.

Three sediment cores (99, 160, 619; see Fig. 1) were collected from isolated basins using a *Hiller peat corer* to study sedimentary successions. The cores are located at elevations of 21.5, 29.5, and 98 m a.s.l., respectively (cores 99, 160, and 619). We collected cores from lakes near the paleo coastlines and from the summit surface to define the upper limit of marine transgression. The sampling was supplemented with lithostratigraphic descriptions. The sampling strategy targeted lithological boundaries and intervals with elevated plant and detrital content for sediment column analysis. The composition of the sediments recovered in the cores appears in Fig. 5 and in Section 4.2.

Boundaries of lithostratigraphic units were targeted for radiocarbon dating (6 dates, Fig. 5, Table 1). Radiocarbon dating was performed using a standard A-B-A procedure of sample pretreatment applied in the Laboratory for Isotope Geochemistry and Geochronology of the Geological Institute of RAS (GIN-index), described in Zaretskaya et al. (2001; 2007). For measurement of ^{14}C activity in the sample, the liquid scintillation counting (LSC) technique was applied. The obtained dates were calibrated using the Calib 8.2 calibration software based on the IntCal20 calibration curve (Reimer et al. 2020).

Diatom analysis of sediments was performed for cores 99 (4 samples), 160 (12 samples), and 619 (5 samples) in the Laboratory of Geoecology of the North, Faculty of

Geography, MSU. Since the number of diatoms in cores 99 and 619 was insufficient, we constructed the diagram only for core 160 (Fig. 6). We collected samples at 10-cm intervals and paid special attention to lithological boundaries that likely mark shifts in depositional conditions.

The processing of samples for diatom analysis was carried out according to the standard procedure (Diatoms of the USSR... 1974): dry sediments were treated with hot hydrogen peroxide (H_2O_2) for 1 h to destroy organic matter; then the samples were washed with distilled water until full removal of H_2O_2 . Permanent slides were prepared on a Naphrax mountant with a refractive index of 1.68. Diatoms were studied under an Axiostar Plus light microscope (Zeiss) with the magnification of $\times 1000$. At least 300 valves were identified to the species level in each sample. The number of diatom valves per 1 g of air-dry sediment was calculated (Davydova 1985). The diatom diagram was plotted using the C2 v. 1.7 software. The names of taxa are given in accordance with AlgaeBase (Guiry and Guiry 2025).

The limited diatom content in the cores resulted in a small sample set. The diatom data served as supplementary evidence, while paleogeomorphological and remote-sensing analyses formed the core of the study.

Geomorphological units (Fig. 2) were identified based on field observations, interpretation of Landsat and QuickBird satellite images (spatial resolution: 15–30 m and 2.4 m, respectively), and digital elevation models (DEMs) or digital surface models (DSMs), in particular, ArcticDEM. It is an automatically produced high-resolution, high-quality digital surface model (DSM) of the Arctic using optical stereo imagery, high-performance computing, and open-source photogrammetry software (spatial resolution: 2 m; Porter

et al. 2023). Also, we used relative-elevation measurements and core data. Mapped units were classified based on the degree of erosion, genetic type, and relative age according to standard geomorphological criteria (Zenkovich 1967; Kaplin et al. 1991; Bird 2008).

RESULTS

Surface topography as an indicator of coastal processes in the Holocene

Based on field observations and remote data (satellite imagery, DEMs), we identified three distinct coastal sectors of the modern Turiy Peninsula (Fig. 2): the southeastern, southwestern, and northwestern (within Sosnovaya Bay).

The *southeastern* sector, exposed to prevailing SE winds, is characterized by sea cliffs and sandy or pebbly beaches. The coast in this part is composed of rocks less resistant to erosion (loose, unconsolidated deposits – usually sands, less often pebbles). This sector shows an alternating pattern: cliffs prevail on headlands, while beaches are found in bays. Sandy and pebbly-sandy shores are formed with a sufficient volume of fine-grained sediments. Where

the supply of fine sediments is limited and glacial material dominates, coarse pebble and boulder-pebble shores are formed. In the northeastern extension of this sector, sandy and pebbly-sandy beaches prevail. This pattern occurs in areas where the sandy tidal flat reaches 50 m in width, and the beach is about 10 m wide.

In the *southwest*, crystalline intrusive rocks resist coastal erosion, and the coastline remains largely unaffected by marine processes. The height of the cliff at Cape Turiy reaches 60–63 m.

The *northwestern* coast is protected from wave action, and tidal flats of various lithologies are common. The width of the tidal flat reaches its maximum (150–200 m) in the apex of Sosnovaya Bay. The coast here is composed mainly of silts enriched in organic detritus.

The modern coast of the Turiy Peninsula provides a clear reference for interpreting the genesis of coastal landforms. Because contemporary coastal forms and the morphology of the uplifted terrain share the same genetic origin, we use modern coastal processes as an analogue for understanding the development of the raised surfaces. The staircase of different-age coastal landforms

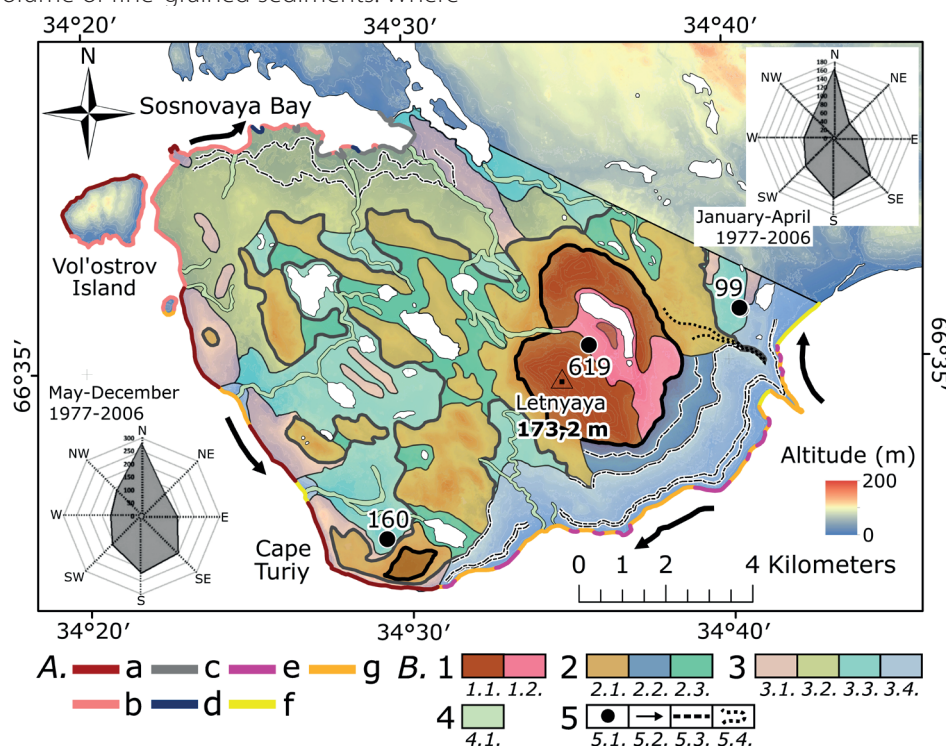


Fig. 2. Geomorphological map of the Turiy Peninsula coast A. Modern coastal types: shores almost unchanged by wave processes: a. primary rocky shores; shores shaped by non-wave processes: tidal shores with different lithology of tidal flat: b. boulder-rock, c. silt and sandy silt, d. mixed type; wave-induced shores: erosional: e. cliffs in sediments of marine terraces, depositional: f. sandy and pebbly-sandy beaches and lagoons, g. pebble and boulder-pebble beaches.

B. Genetic types of landforms: 1. Surfaces without traces of coastal processes at heights of more than 90 m a.s.l.: 1.1. Structural landforms with fragmentary sediment cover, 1.2. Structural gently sloping plain partially overlain by glacial and glaciofluvial deposits; 2. Surfaces reworked by coastal processes during the Late Glacial transgression, and during the existence of the Early and Middle Holocene sea at altitudes of 50–90 m a.s.l.: 2.1. Structural ridges and massifs with fragmentary sediment cover, practically unchanged by wave processes, 2.2. Inclined wave-cut platforms transformed by coastal processes with a thin cover of marine sediments and a series of beach ridges, 2.3. Structural basins of paleostraits and bays filled with marine and lacustrine-marsh deposits; 3. Surfaces affected by coastal processes during the existence of the Middle-Late Holocene sea at altitudes less than 50 m a.s.l.: 3.1. Structural ridges and massifs with fragmentary sediment cover, practically unchanged by coastal erosion, 3.2. Stepped structural denudational surface transformed in the coastal zone with the predominance of non-wave processes (tides; shore-fast ice exposure; biogenic processes etc.) with a fragmentary sediment cover, 3.3. Structural basins of paleostraits and bays filled with marine and lacustrine-marsh deposits, 3.4. Inclined wave-cut platforms created by wave processes and composed of sand and gravel-pebble deposits, accompanied by a series of beach ridges; 4. Fluvial landforms formed after coastline retreat: 4.1. Slightly incised erosional landforms; 5. Other designations: 5.1. Positions of sediment cores, 5.2. Sediment flow direction, 5.3. Coastlines, 5.4. Separated structural ridges. Digital basis – 2-meter ArcticDEM (Porter et al. 2023). The wind rose indicates the frequency of wind directions according to the Umba hydrometeorological station for the periods of May-December and January-April 1977–2006 (ESIMO 2007)

on the southeastern terraces of the peninsula reflects this continuity and forms the basis for reconstructing Holocene coastline evolution. Analysis of the uplifted terrain shows that higher-level landforms closely replicate those found on the present coast, especially along the wave-exposed southeastern coastline, which preserves the most complete archive of coastal change.

We identified these coastal landforms at altitudes of 10, 22–23, 47–49, 69–70, and ~90 m a.s.l. Beach ridges at altitudes of up to 50 m a.s.l. are composed of sand and gravelly-sand sediment and mostly parallel the coastlines. A dense sequence of ridges at ~20 m a.s.l. (Fig. 3) suggests a period of intensified wave activity. Above ~50 m a.s.l., beach ridges become rarer and less distinct, with the highest traces of erosional modification observed at ~90 m a.s.l. on the southeastern slope of Letnyaya Mountain.

In the northwest of the peninsula, at comparable elevations (up to 90 m a.s.l.), the surface consists of irregular, poorly leveled marshy steps containing lakes, and remnants of glacial ridges. By their morphology, these surfaces resemble modern tidal flats. The scarps are not consistently expressed and occur at variable elevations,

with the most distinct ones observed at 10 and 22 m a.s.l. The southern part of the peninsula forms a steep, nearly vertical rock scarp reaching up to 60–63 m a.s.l.

The summit surface of the peninsula, above 90 m a.s.l., consists of structural ridges and massifs and glacial features (Fig. 2). At these elevations, including the southeastern part of the peninsula, we did not identify any coastal landforms. Instead, we observed rounded boulders and clusters of boulders occurring at various heights (Fig. 3).

Morphological evidence implies that most of the peninsula once represented a skerry-type landscape, comprising bedrock islands and intervening straits (Fig. 4). Currently, these paleobays and paleostraits appear as gently sloping, waterlogged lowlands. This type of landscape is traditionally classified as a fiard-skerry (Safianov and Solovieva 2005).

Lithology and chronology of isolated lakes

We distinguished six lithological units in the studied sedimentary successions, as shown in Fig. 5. Core 99 is located at the extreme northeastern part of the peninsula

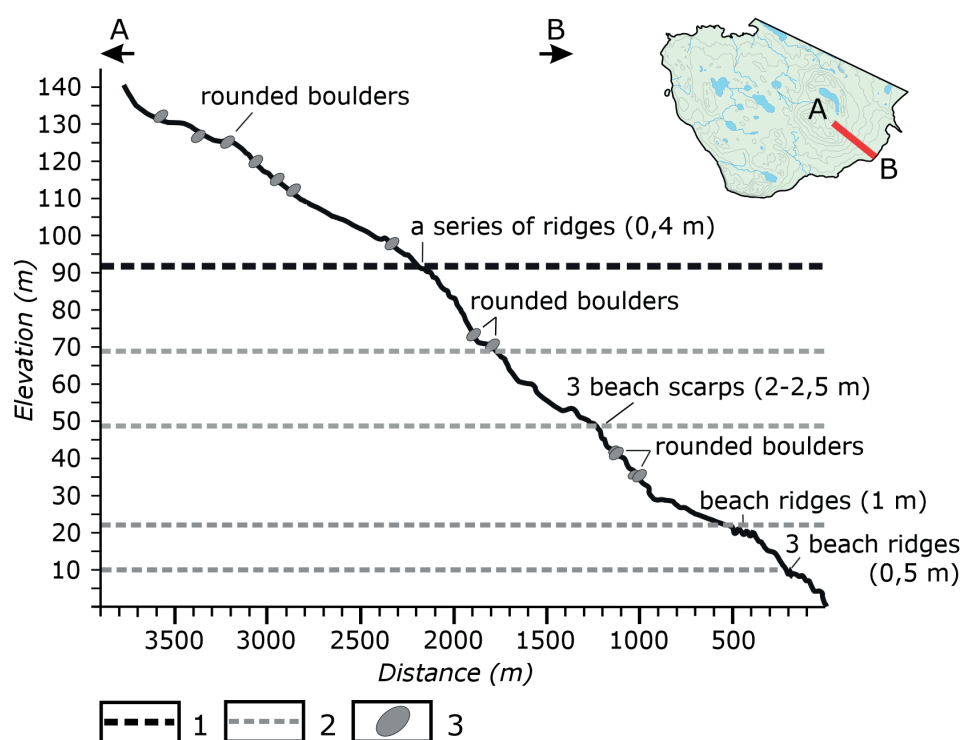


Fig. 3. Topographic profile of Letnyaya Mountain southeastern slope according to the results of field investigations: 1 – ancient coastlines, 2 – upper limit of the traces of wave reworking (erosional or accumulative), 3 – rounded boulders as indicators of marine or glacial impact



Fig. 4. Skerries of Kandalaksha Bay (vicinity of the Luvenga rural locality, Murmansk Region, NW Russia; photo by Alena Yakovleva)

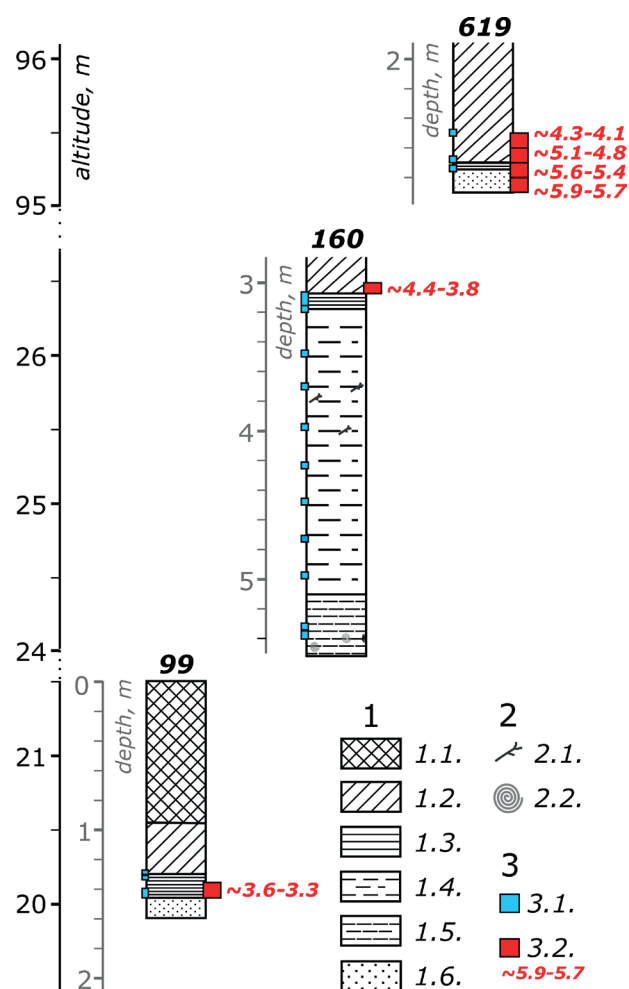


Fig. 5. Lithostratigraphy and chronology of the studied sediment cores: 1. lithological units: 1.1. – peat, 1.2. – silty peat, 1.3. – interbedding of silt and peat, 1.4. – silty gyttja, 1.5. – silt, 1.6. – sand, 2. organic detritus: 2.1. – shell detritus, 2.2. – plant detritus, 3. Other: 3.1. diatom sampling site, 3.2. radiocarbon sampling site and age in cal ka BP. The scale to the left from lithology shows the depth from the water surface (for sedimentary successions 99 (21.5 m a.s.l.), 160 (29.5 m a.s.l.), 619 (98 m a.s.l.)) and depth below the peat layer top in m.

at an elevation of 21.5 m a.s.l. The core was collected from a marshy surface that formerly represented a paleobay, separated from the sea by a beach ridge. The presence of the beach ridge confirms past marine influence at this level, as does the sediment succession revealed in the core. The core has a thickness of 1.6 m and exposes the following sedimentary sequence: beneath the lacustrine-marsh deposits, composed of peat and silty peat typical of freshwater lakes, we encountered sediments consisting of well-sorted sands. The transitional layer, represented by interbedding of peat and silt with sand, was selected for radiocarbon dating. It yielded an age of $\sim 3.6\text{--}3.3$ cal ka BP. Core 160 was taken from a low-lying, marshy part of the terrace at an elevation of 29.5 m a.s.l. It has a structure similar to that of core 99. This section is the most representative and has a thickness of 5.5 m. Its sedimentary succession, from top to bottom, includes peat, silty peat, interbedded peat and silt, silty gyttja with plant detritus, and silt. A radiocarbon age of $\sim 4.4\text{--}3.8$ cal ka BP was obtained from the transitional layer. Core 619 is located at an elevation of 98 m a.s.l. and was selected to determine the upper marine limit. Its thickness is 2.9 m. The upper two units are composed of lacustrine-marsh peat and silty peat. The top of the silty peat yielded radiocarbon ages of $\sim 4.3\text{--}4.1$ and $\sim 5.1\text{--}4.8$ cal ka BP. The transitional layer, represented by interbedded silt and peat, produced an age range of $\sim 5.6\text{--}5.4$ cal ka BP. The bottom of the section consisted of peaty sands and yielded an age of $\sim 5.9\text{--}5.7$ cal ka BP.

Below, we present the diatom assemblages from all three cores to examine past sedimentary conditions (Fig. 6).

The silty peat at the bottom of core 99 (1.45–1.33 m) contains diverse diatom associations (47 species per 300 valves) with high concentration (~ 80 million valves per gram). Chrysophyte cysts are present in smaller amounts of 3 thousand per gram. Diatoms are solely represented by freshwater species characteristic of small lakes with low electrolyte content and low pH values: *Stauroforma*, *Eucocconeis flexella*, *Eunotia* spp., *Brachysira* spp. In the gyttja (1.33–1.30 m), the diatom concentration is significantly higher – 1.5 billion valves per gram, and their taxonomic diversity is similar to the underlying layer (43 species per 350 valves). The most common species are *Stauroforma exiguiformis*, *Brachysira* spp., *Tabellaria* spp., and other species typical of northern dystrophic lakes.

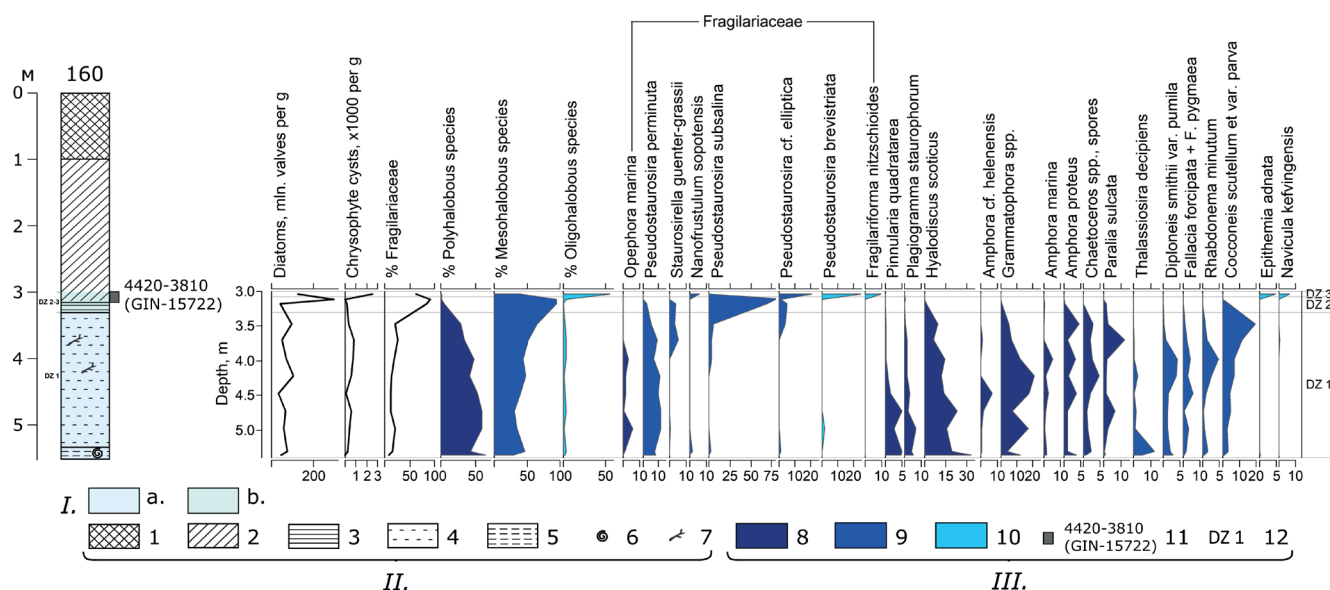


Fig. 6. Diatom diagram of core 160. I. Salinity: a. marine conditions, b. transitional (from marine to freshwater) conditions. II. Lithology: 1 – peat, 2 – silty peat, 3 – interbedding of silt and peat, 4 – silty gyttja, 5 – silt, 6 – shell detritus, and 7 – plant detritus. III. Characteristic of species according to Hustedt's halobous system (1957): 8 – polyhalobous, 9 – mesohalobous, 10 – oligohalobous. IV. Other: 11 – calibrated age, cal yrs BP, 2σ (95.4%), 12 – Diatom Zones (DZ)

The concentration of Chrysophyte cysts increases to 54 thousand per gram. Up the core, at the base of the peat layer (1.3–1.28 m), the number of diatom valves reaches its maximum (3 billion valves per gram) along with a sharp decline in taxonomic diversity (23 species per 400 diatom valves). The concentration of Chrysophyte cysts decreases to 9 thousand per gram. The dominant species are *Stauroforma exiguiiformis* (74%) and *Aulacoseira alpigena*. *A. alpigena* is a cosmopolitan meroplanktonic species preferring oligotrophic water bodies with low electrolyte content. This species is widespread in the plankton of oligotrophic lakes and rivers of northern Europe, including the Kola Peninsula (Letanskaya 1974; Nikulina 1975; Kagan 2012).

Thus, we can conclude that all recorded species are freshwater ones. No species indicating a connection between the water body and the sea or proximity to the sea were revealed by diatom analysis of core 99. The species composition corresponds to a small dystrophic lake. The oligodominant nature of diatom associations with a very high concentration of valves and taxonomic diversity decreasing up the section provides evidence of lake overgrowth. The onset of the accumulation of organogenic lake sediments according to radiocarbon dating is 3640–3330 cal yrs BP (GIN-15721) (Table 1).

Diatom data from core 160 (29.5 m a.s.l.) are more representative (Fig. 6). Three DZs were distinguished based on diatom species composition and abundance. In DZ 1 covering the lower part of the section (5.4–3.3 m) the concentration of diatoms is high, varying between 30 and 100 million valves per gram. Chrysophyte cysts are found sporadically, in concentrations of less than 1000 cysts per gram. Taxonomic diversity of diatoms is 44–61 species per 300 valves. Diatom associations consist predominantly of marine and brackish-water benthic and meroplanktonic species: *Hyalodiscus scoticus*, *Thalassiosira decipiens*, *Paralia sulcata*, *Grammatophora* spp., *Amphora* spp., and *Pseudostaurosira perminuta*, among others. The proportion of polyhalobous species (according to the classification of Hustedt (1957)) decreases up the section (65–29%), while that of mesohalobous species increases from 29 to 66%.

DZ 2 (3.3–3.08 m) corresponds to the upper part of the bluish-gray silt, interlayered with peat beds. The concentration of diatoms increases from 40 to 300 million valves per gram with low taxonomic diversity, 24–16 species per 300 valves. Chrysophyte cysts are rare, <200 cysts per gram. The composition of diatom associations is monodominant: 70–84% of valves belong

to *Pseudostaurosira subsalina*, a brackish-water species abundant on salt marshes and in microbial mats of the Baltic and North seas (Witkowski et al. 2000), where it is recognized as one of the best indicators of littoral and supralittoral environments. The total sum of small-cell brackish-water species of the Fragilariaceae family (*Pseudostaurosira subsalina*, *P. cf. elliptica*, *P. perminuta* and *Staurosirella guenter-grassii*) reaches up to 85–91% of all valves.

DZ 3 (3.08–3 m) corresponds to the basal part of the peat layer. The concentration of diatoms is high – 125 million valves per gram. Chrysophyte cysts have a significantly higher concentration than in the underlying sediments, equal to 2.5 thousand cysts per gram. Similar to DZ 2, small-cell species of the Fragilariaceae family also predominate, but their share is lower (62%), and the composition is mixed: mesohalobous *Pseudostaurosira cf. elliptica* and *Nanofrustulum sopotensis* co-occur with oligohalobous *Pseudostaurosira brevistriata* and *Fragilariforma nitzschioides*. Oligohalobous *Navicula kefvingensis* and *Epithemia adnata* are also among the dominants. Taxonomic diversity is higher than in DZ 2 (38 species per 300 valves), which may be due to the mixing of the brackish-water and freshwater components of diatom associations.

Thus, the dominance of marine and brackish-water benthic species and the absence of holoplanktonic species among the dominants in DZ 1 indicate sedimentation in the relatively shallow coastal zone of the sea. The predominance of species with heavily silicified valves that are commonly attached to the substrate and are typical of the littoral zone with an active hydrodynamic regime points to sedimentation in the middle part of the tidal flat open to the sea. The mass development of small-cell colonial species of the Fragilariaceae family in DZ 2 indicates sedimentation in a calm hydrodynamic environment in shallow waters (Weckström and Juggins 2005; Repkina et al. 2023). Diatoms probably developed on macrophytes and in microbial mats in the upper part of the tidal flat, probably in lagoon environments. Marine depositional conditions are indicated by the continued dominance of brackish-water species and the minor presence of freshwater species. DZ 3 highlights transitional environments from marine to continental ones. This transition is dated to the time interval 4420–3810 cal yrs BP (GIN-15722) (Table 1).

In core 619 located at an altitude of about 98 m a.s.l. (Fig. 1) in the area of Lake Letnegorskoe, the horizon of dark

Table 1. Radiocarbon data and calibrated age estimations of the studied core sediments

#Core / #lithological unit (Fig. 5)	Altitude of the sampling point, m	Sampling interval, m	Laboratory code	14C date, yrs BP	Calibrated age, cal yrs BP, 2σ (95.4%), mean	Lithological description
99/4	21.5	1.45–1.35	GIN-15721	3240 ± 80	[3640–3330], 3460	Brownish silty peat with sand
160/3	29.5	3.15–3.05	GIN-15722	3720 ± 130	[4420–3810], 4070	Brownish silty peat
619/3.1	98	2.6–2.5	GIN-15918	3820 ± 30	[4300–4140], 4200	Dark brown peat with sand
619/3.2	98	2.7–2.6	GIN-15917	4390 ± 60	[5070–4840], 4970	Dark brown peat with sand
619/4-5	98	2.8–2.7	GIN-15916	4840 ± 40	[5610–5480], 5590	Dark brown peat with sand
619/5	98	2.9–2.8	GIN-15915	5090 ± 40	[5920–5740], 5800	Dark brown peat with sand

brown peat that dates back to the Middle-Late Holocene (Table 1). It is possible to assume that such a young age for this altitude is a consequence of a considerable time gap between the drainage of the basin and the subsequent formation of the sediments. The basal core sands are barren of diatoms. Higher up the section, in the peat, rare bog species *Eunotia* spp. and *Pinnularia* spp. are noted. Thus, the data of diatom analysis from this core confirm freshwater conditions.

DISCUSSION

Paleogeographic environments during the formation of ancient coastlines

Lithology and wave climate conditions often play a decisive role in the formation of different coastal types. Waves, winds, and currents are the primary drivers of coastal processes. In this case, the presence of a sediment cover and its degree of resistance to coastal erosion are also critical factors influencing coastal evolution (Zenkovich 1967; Bird 2008). In general, glacial and less often glaciofluvial deposits of the Late Valdai glaciation (the last glaciation of the East European Plain) form the basis of coastal landforms in the White Sea (Safianov and Solovieva 2005). Nevertheless, the thickness of the Quaternary deposits within Kandalaksha Bay is relatively small (Astafiev et al. 2012). In places where the bedrocks of the Baltic Shield are exposed, rocky shores resistant to erosion are formed. If there is a cover of loose sediments, the course of coastal processes is primarily governed by wave climate conditions. The Turiy Peninsula in this case represents a good case study where all of the above patterns are observed.

The well-developed series of coastal landforms within the southeastern coast of the Turiy Peninsula were formed as a result of long-term environmental changes such as sea-level change, postglacial uplift (Baranskaya 2018, 2024; Kolka and Korsakova 2017; Korsakova 2022) or wave climate changes (Repkina et al. 2020). Wave climate changes within the White Sea coast can be assessed based on the duration of the ice-covered period (Polyakova et al. 2023). The morphology of coastal landforms can also be used as an indirect indicator of wave climate changes (Kaplin and Selivanov 1999). The interpretation of beach ridges as indicators of depositional or erosional phases is supported by previous research (Zenkovich 1967; Bird 2008) and was used here to reconstruct coastal morphodynamics. Multiple ridges indicate prolonged depositional activity, while gently sloping areas between ridges may signal transitions to erosion-dominated phases.

A morphological criterion for identifying traces of wave reworking (erosional or depositional) of the surface is the presence and regularity of beach ridges (Kaplin and Selivanov 1999). However, this approach provides information only on the relative age of the landforms. In addition, wave-reworked landforms can be destroyed by other erosional processes or by anthropogenic impacts, so some information may be lost. The combination of numerical dating and diatom analysis provides a means to establish the formation age of coastal landforms. Analysis of landform distribution within uplifted land and the modern coastal zone, supported by the results of radiocarbon dating and diatom analysis, allows us to reliably identify a marine-reworked geomorphological level of the uplifted coast up to 26.5 m a.s.l. (calculated as the top of core 160 minus the peat thickness). We also assume that the marine basin did not reach altitudes above 90 m a.s.l. due to the absence of coastal landforms as well as marine diatoms in core 619. Geomorphological levels are identified based on landform

characteristics. Below, we provide descriptions of the morphology of each identified geomorphological level and relate their formation to known stages of paleogeographic changes that could have influenced wave dynamics in the area. In this way, we can approximately estimate the ages of geomorphological levels for which numerical dating is not available.

At altitudes of more than 90 (100) m a.s.l., a discontinuous cover of glacial and glaciofluvial deposits is developed (Astafiev et al. 2012; Kolka et al. 2013), which is “washed away” at lower altitudes and reworked by coastal erosion. During our field observations and interpretation of the satellite images, we did not find any traces of wave reworking of landforms elevated above 90 m a.s.l. However, according to other data (Kolka et al. 2013), 3 beach ridges were found at the altitude of 103 m a.s.l. Hence, we can conclude that they occur sporadically. There is an assumption (Kolka et al. 2013) that such high beach ridges and terraces may correspond to coastlines of a former proglacial lake. Further evidence for this is the mosaic pattern of such landforms. Thus, formation of this level corresponds to harsh climatic and glacial conditions of the early stages of deglaciation (Kolka et al. 2013; Polyakova et al. 2023). However, we cannot assert this confidently.

At elevations of 90–70 m a.s.l., we identified sporadic beach ridges on the southeastern slope of Letnyaya Mountain up to 90 m (Fig. 3) during our investigations. These landforms record a phase of coastal processes at this level. Formation of these beach ridges likely occurred after the deglaciation of the peninsula, i.e., later than ~12.5 cal ka BP (Astakhov et al. 2016), under conditions of rapid RSL fluctuations during the Late Glacial transgression (~13.4–11.6 cal ka BP) and regression of the Early Holocene (~11.6–9.5 cal ka BP) (Korsakova 2022). During this period (~13.5–11.5 cal ka BP), the White Sea experienced rapid changes in hydrological conditions (Polyakova et al. 2014). Starting from ~11.7 cal ka BP, a strong current transporting modified Atlantic waters along the Tersky Coast to Kandalaksha Bay became well established (Polyakova et al. 2023). With the ongoing deglaciation, the climate gradually warmed.

Climate warming is also evidenced by reconstructions derived from terrestrial archives. Younger Dryas – early Holocene vegetation in the southern Kola Peninsula consisted of forest-tundra communities with dwarf birches (Elina et al. 2000; Kotlyakov et al. 2014), that were subsequently replaced by birch forests. Since ~10 cal ka BP, pine forests indicative of warm and humid conditions became common (Kremenetski and Patyk-Kara 1997; Sapelko 2009; Grekov et al. 2013b). A warming climate and less extensive sea ice cover facilitated the activation of coastal processes reflected in morphology at this level.

Beach ridges at 70–50 m a.s.l. are more frequent and have better preservation than those at higher altitudes. Judging from the surface morphology, the landforms at this level were transformed by the sea with more intense wave action and less extensive seasonal sea-ice cover compared to the present conditions. Marine deposits are characterized by poorer sorting compared to those at lower levels. According to the reconstructions by Polyakova et al. (2023), this sea basin likely existed from ~8.6 to 6 cal ka BP (Polyakova et al. 2023), during the Tapes transgression (Korsakova 2022). Paleolandscape reconstructions along the Tersky Coast (Lake Berkut surroundings) indicate that the Turiy Peninsula area may have experienced relatively warmer and more humid than present conditions during this period until 7 cal ka BP (MacDonald et al. 2000; Ilyashuk et al. 2005). This is also confirmed by reconstructions from the area adjacent to the Turiy Peninsula – the Lake

Kanozero area, where middle taiga landscapes were common (Sapelko et al. 2022).

Recent reconstructions (Ludikova et al. 2022) suggest that the level of the Late Glacial transgression exceeded 52.7 m a.s.l. within Kanozero Lake, while on the Turiy Peninsula, the morphology of the beach ridges at elevations of 50–70 m a.s.l. identifies this level as part of the warm sea of the Tapes transgression (9.5–6.8 cal ka BP).

Surfaces below 50 m a.s.l. morphologically resemble modern coastal landforms. We confirm that terraces of this geomorphological level formed at the end of the Middle-Late Holocene (probably later than 6 cal ka BP) based on the obtained data and available reconstructions (Polyakova et al. 2023). Apparently, the landforms were formed under conditions characterized by seasonal sea-ice cover of short duration. This led to the activation of wave processes. Episodes of high wave activity during this period were also reconstructed in other areas of the White Sea (Nevesskii et al. 1977; Zaretskaya 2018; Repkina et al. 2020), and are indirectly confirmed by the morphology of the Turiy Peninsula coast. The highest and most frequent beach ridges are found within this level (Fig. 3).

Terrestrial climate conditions gradually shifted from the warmest during the Holocene climate optimum towards modern-like. Some cooling occurred at the boundary of the Middle and Late Holocene (Elina et al. 2000). Northern taiga and bogs were widespread in the area of the Turiy Peninsula in association with the slight climate cooling (Sapelko et al. 2022), whereas the waters of the White Sea remained sufficiently warm (Polyakova et al. 2023). Since 1.5 cal ka BP, vegetation assemblages have become similar to modern communities (Elina et al. 2000; Kotlyakov et al. 2014).

The results of radiocarbon dating, lithological, and diatom analyses of sediments from the isolated basins (cores 160 and 99) allowed us to date the coastline positions at 29.5 and 21.5 m a.s.l. (Fig. 6, Table 1). Changes in sediment composition, as well as transitions in the taxonomic composition of diatoms within these basins, probably confirm the existence of residual water bodies in the past. The transition of diatom associations in these basins was probably influenced by both changes in salinity and alterations in the hydrodynamic regime during the isolation of a water body. Judging by the obtained age estimations, the separation of these reservoirs from the sea occurred approximately 4420–3810 cal yrs BP (160/3, Table 1) at 29.5 m a.s.l. and earlier than 3640–3330 cal yrs BP (99/4, Table 1) at 21.5 m a.s.l.

Our results also demonstrate that three morphologically distinct coastal sectors existed throughout the postglacial regional history – the wave-dominated southeastern, primary southern (without traces of wave processes) and tidal northwestern ones (Fig. 3). Modern coastal landforms share the same genetic origin as the uplifted landforms. Based on this, we conclude that changing paleogeographic conditions during the postglacial period had virtually no effect on the morphology of the northwestern coast. Thus, we can conclude that shore exposure to the prevailing wave direction is crucial for its evolution. The presence of loose sediments is equally important in shaping the general appearance of the coast. They provide the material necessary for the formation of coastal landforms, and in their absence, distinct coastal relief cannot form. A clear example of this is the rocky southern coast: although its position is favorable for wave action and it could potentially develop coastal landforms, it contains virtually no landforms due to the absence of loose sediments. Using the Turiy Peninsula as a case study, a notable transition from wave-dominated

to tide-dominated coasts, as exposure shifted to the prevailing wave direction along the coastline, was clearly observed for the first time in the White Sea region.

Postglacial movements

The postglacial evolution of the White Sea has been largely shaped by spatially variable glacioisostatic uplift and ongoing neotectonic activity within its basin, reflecting complex interactions between glacial unloading, isostatic adjustment, and regional tectonics. Tectonic movements across the Baltic Shield exhibit a block-structured pattern (Nikonov 1964; Shvarev 2022; Baranskaya 2024). Different movement rates are reported for individual tectonic blocks (Repkina and Romanenko 2016; Kolka and Korsakova 2017; Korsakova 2022). For instance, along the Karelian Coast of the White Sea, differences in uplift rates of up to 5–6 mm/year between macroblocks have been documented (Baranskaya et al. 2019).

The results of radiocarbon dating and diatom analysis allowed us to estimate the Turiy Peninsula uplift rate for the last ~3.5–4 cal ka at 5–7 mm/year. This value significantly exceeds the estimated uplift rate in the adjacent Umba settlement, where rates of ~3.8 mm/year have been reported for the same period (our calculations based on Kolka et al. (2013a)). These results support the interpretation of block-structured tectonic uplift across the Turiy Peninsula.

The stark contrast in uplift rates between adjacent regions highlights the importance of local tectonic configuration and the underlying lithospheric response to deglaciation. Such spatial variability underscores the need for high-resolution reconstructions when interpreting coastline displacement patterns. These differential uplift rates are also consistent with the distribution and preservation of coastal landforms across different altitudes, suggesting a close link between neotectonic activity and morphogenesis. Understanding these localized uplift dynamics is crucial for refining regional RSL curves. Therefore, the Turiy Peninsula exemplifies how postglacial tectonic block movement can significantly alter coastal evolution trajectories even at local scales (Baranskaya et al. 2019).

CONCLUSIONS

This study identified four geomorphological levels on the Turiy Peninsula, distinguished by their elevation, age, and formation conditions:

- At altitudes above 90–100 m a.s.l., no clear coastal landforms were identified.
- Landforms at 70–90 (100) m a.s.l. likely formed under conditions of rapid RSL fluctuations during the Late Glacial transgression and Early Holocene regression.
- The coastal zone at 50–70 m a.s.l. was shaped by a relatively ice-free sea that existed from ~8.6 to 6 cal ka BP.
- Surfaces below 50 m a.s.l. were formed in the Middle-Late Holocene, likely after ~6 cal ka BP, according to the data from adjacent areas. Their formation reflects conditions increasingly similar to the modern environment. Our paleogeomorphological reconstructions, supported by radiocarbon dating and diatom analysis, confirm their marine origin at elevations up to 26.5 m a.s.l. for the period prior to ~3.5–4 cal ka BP.

The Turiy Peninsula can be divided into three morphologically distinct coastal sectors: a wave-dominated southeastern coast, a southern coast lacking evidence of wave activity, and a tide-influenced northwestern coast.

The topography of uplifted land generally reflects the spatial distribution of modern coastal types. This indicates that modern coastlines inherit their morphology from earlier paleogeographic conditions. Where unconsolidated sediments are present, coastal type is primarily controlled by exposure to prevailing wave directions; where such sediments are absent, bedrock lithology becomes the dominant factor.

The identified geomorphological levels correspond to the key stages in the postglacial evolution of the peninsula. Rapid postglacial uplift was the primary driver shaping the current distribution of coastal landforms. The coastline

emerged rapidly from the zone of active wave influence, which limited the reworking of older coastal landforms.

The uplift rate of the Turiy Peninsula (5–7 mm/year over the last ~3.5–4 cal ka) exceeds those of the surrounding areas, supporting the hypothesis of block-structured tectonic behavior in the region.

The Turiy Peninsula example highlights that coastal morphology is primarily shaped by wave exposure and substrate availability. When exposure to wave energy decreases, the coastline rapidly transitions into a tide-dominated regime. ■

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SPATIOTEMPORAL VARIABILITY OF PALMER DROUGHT SEVERITY INDEX INFERRED FROM LONG TREE-RING CHRONOLOGIES IN THE RUSSIAN AND MONGOLIAN PARTS OF THE LAKE BAIKAL BASIN

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ABSTRACT. The spatiotemporal variability of moisture conditions in the Lake Baikal basin, a key region of Inner Asia, remains insufficiently understood due to the short duration of instrumental observations and the complex interplay of climatic factors. In this study, we reconstructed the self-calibrating Palmer Drought Severity Index (PDSI) for May–July using four long tree-ring chronologies from the Russian and Mongolian parts of the Baikal basin. Linear models explain 34–57% of the interannual variance in the instrumental PDSI. The 11-year smoothed mean PDSI values reveal alternating periods of in-phase and out-of-phase moisture variability between the two parts of the basin over the past ~250 years, while long-term (30-year) series show divergent trends: increasing moisture availability in the northern (BRG) and southwestern (HEC) parts of the basin and intensifying aridization in the central-southern part (KST, KRN). Several extreme drought (1863, 1923, and 2003) and wet (1938) years with broad spatial extent were identified. Spectral analysis of the reconstructed series revealed significant cycles of approximately 2–5 years and 14–56 years. The results of this study demonstrate substantial spatial heterogeneity in drought dynamics and highlight the influence of both local and large-scale climatic factors on moisture regimes in Baikal Asia.

KEYWORDS: PDSI reconstruction, dendroclimatology, drought, floods, Baikal Asia

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INTRODUCTION

Climate change in Russia is evidenced by a rate of warming more than twice the global average, a trend expected to continue in the 21st century (Roshydromet 2014; Edelgeriev et al. 2021). Anthropogenic influences are expanding arid zones and intensifying extreme heat and precipitation events. Extreme climatic phenomena – heat waves, droughts, floods, wildfires, etc. – significantly impact ecosystems; in Asia, these effects are especially acute due to high drought vulnerability¹. However, confidence in drought trend assessments remains low because of limited long-term observations, inconsistent definitions, and spatial heterogeneity. Drought, as a natural phenomenon, lacks clear temporal and spatial boundaries, since its intensity is hard to define and measure (Wilhite and Glantz 1985).

Drought impacts are particularly critical in arid and semi-arid regions. The Lake Baikal basin, spanning parts

of Russia and Mongolia, also experiences droughts. A hydrological drought since 1995 has reduced the annual flow of the Selenga River, the main tributary of Lake Baikal. Consequently, suspended sediment transport changed (Chalov et al. 2015; Kasimov et al. 2020), the unique Selenga River delta's barrier functions deteriorated (Chalov et al. 2016; Frolova et al. 2017b), and Lake Baikal's water level regime was disrupted (Alymbaeva et al. 2024).

Regular weather observations in the Russian Baikal basin began in the late 19th century and expanded in the 1930s–1950s. Mongolia's hydrometeorological service started in the mid-20th century. Thus, instrumental data alone cannot fully capture the duration and intensity of historical droughts. Trees with distinct annual rings in harsh climates act as natural “meteorological stations”: in arid environments, ring widths closely reflect site moisture and are widely used to reconstruct droughts centuries into the past (Tabakova et al. 2020). For the quantitative assessment of moisture conditions, one of the key indicators is the

¹IPCC, 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani (eds.)]. In Press.

Palmer Drought Severity Index (PDSI), which is widely applied in dendroclimatic reconstructions and reflects a close relationship with tree-ring width in the arid territories of Russia (Kuznetsova and Pozhidaeva 2017; Shigimaga et al. 2024) and Asia (Cook et al. 2010).

Over the past decades, numerous studies have been conducted in the Mongolian part of the Lake Baikal basin to reconstruct moisture variability, river runoff (Davi et al. 2006; Pederson et al. 2001; Leland et al. 2013; Davi et al. 2013), and the PDSI (Davi et al. 2010; Pederson et al. 2014; Haraguchi et al. 2022). In contrast, substantially fewer such studies have been carried out in the Russian part of the basin (Andreev et al. 1999; 2001; Demina et al. 2017; Belokopytova et al. 2018), and studies specifically devoted to PDSI reconstruction based on long chronologies are lacking. At the same time, no previous comparative analysis of the variability of this index across different parts of the Lake Baikal basin has been conducted.

The present study provides the first spatiotemporal reconstruction of the PDSI encompassing the entire Baikal basin. The research objectives are as follows: 1) to reconstruct and compare the history of droughts in the Russian and Mongolian parts; 2) to identify long-term trends and extreme events; 3) to assess the spatial heterogeneity of the moisture regime in different parts of the basin.

MATERIAL AND METHODS

Study Area and Climate

The Lake Baikal basin lies in Inner Asia and covers 545,000 km² (excluding the lake area). About 45% of the basin's area is in Russia and 55% in Mongolia. The basin extends over 1300 km from south to north and up to 800 km from west to east at its widest point, in the Mongolian part. The climate of Baikal Asia is sharply continental, with large annual and diurnal temperature ranges and uneven seasonal precipitation. Mean annual air temperatures range from −0.1 °C in the south to −6.7 °C in the north; January is the coldest month, July – the warmest. The mountainous terrain causes complex precipitation patterns: the lowest annual totals (250–400 mm) fall in the steppes and valleys, while the highest totals (>1000 mm) occur in the mountains (e.g., Khमार-Daban Range). Up to 90% of precipitation occurs in summer and autumn as rain, except in the northern basin, where 30–50% is snow (Garmaev 2010).

Vegetation comprises three main types: alpine, boreal (taiga), and steppe. Boreal forests extend far south

along ranges, while steppes spread northward through intermontane basins. Forests cover much of the region (mean forest cover ~62.5% in the Russian part vs ~11.5% in the Mongolian part). Coniferous species (pine, larch) dominate, with some birch and aspen (Ecological Atlas... 2015).

Tree-Ring Chronologies

This study uses chronologies from the Barguzin, Uda, and Chikoy river valleys (Russian part) and the Ider Valley (northwestern Mongolia), covering diverse climatic zones of the Baikal basin. We selected the longest available chronologies from forest-steppe sites to maximize drought history coverage (Fig. 1). Sampling and core analysis followed standard dendrochronological methods (Vaganov et al. 1996). We extracted cores from living trees using an increment borer, targeting dominant species in the study area: Scots pine (*Pinus sylvestris* L.) and Siberian larch (*Larix sibirica* Ledeb.). All chronologies were built from cores of living trees collected in 2016–2019 field campaigns, about one-third of which were old-growth individuals.

The KST chronology was extended back to 1498 CE using historical wood from an ethnographic museum building (Andreev et al. 2022). The KRN chronology was extended to 1608 CE using wood from an old house (19th-century heritage site) in the city of Kyakhta.

Ring widths were measured using a LINTAB 5 system with a precision of 0.01 mm. Crossdating and identification of false/missing rings were performed in TSAP-Win; dating quality and statistics were checked with COFECHA software. Series with low coherence were removed based on interseries correlation (R_{bar}) criteria. All chronologies (including those extended with historical wood) were standardized uniformly: age trends were removed with negative exponential or cubic spline fits (ARSTAN software). We then derived the Tree-Ring Index (TRI) from these standardized series. Residual chronologies (with autocorrelation removed) were used for climate reconstruction, as they preserve high-frequency variations and showed the highest predictive skill in split-period validation.

Chronology quality was evaluated using mean interseries correlation (R_{bar}), mean sensitivity (MS), standard deviation (SD), and expressed population signal (EPS). EPS was calculated for 51-year windows with 25-year overlap. It indicates periods when sample depth is sufficient for high-accuracy climate reconstruction (common signal exceeds noise), usually requiring $EPS > 0.85$.

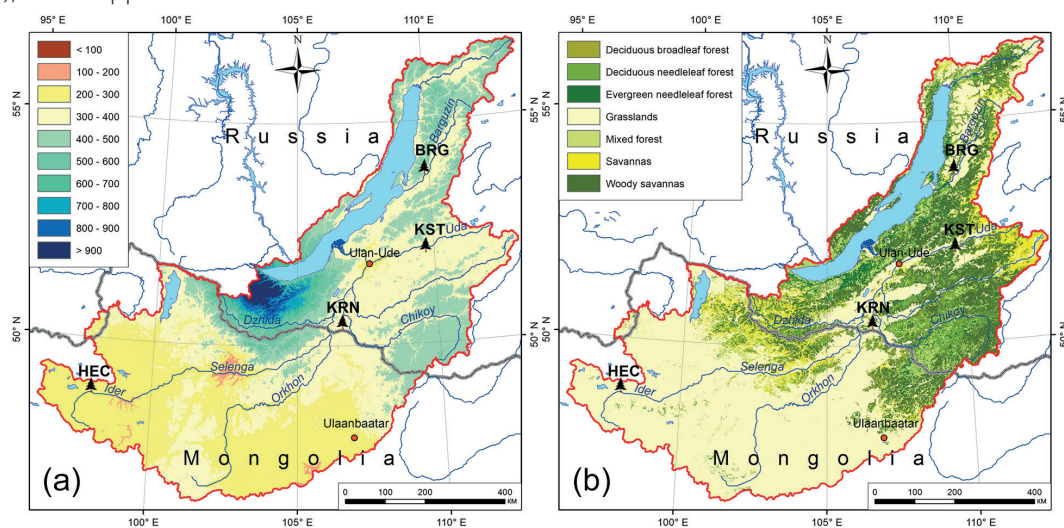


Fig. 1. Study area: (a) mean annual precipitation (mm); (b) landscape types (forest, forest-steppe, steppe, etc.) in the Baikal basin, along with locations of the tree-ring chronologies

Climate Data

We used climatic data from CRU TS 4.06 (0.5° grid, period 1931–2016), obtained via the KNMI Climate Explorer². For each site, mean monthly temperature, precipitation, and the self-calibrating PDSI (scPDSI) were extracted from the grid cells closest to the tree-ring chronologies exhibiting the highest correlations. The PDSI is based on a monthly climatic water balance model, determined by precipitation, temperature, and local soil water-holding capacity (Palmer 1965). The PDSI, derived from CRU TS data, is widely used as a gridded target variable in drought studies (van der Schrier et al. 2013). However, the accuracy of CRU TS depends on the density of the meteorological network; a sparse network can smooth out extremes, reduce variance, and distort trends (Harris et al. 2020). Therefore, the calibration of tree-ring chronologies with PDSI should be interpreted as a response to the grid-cell-averaged moisture signal, rather than as a point-by-point comparison with a specific station. Nevertheless, most of the tree-ring chronology sites are located near meteorological stations, which supports the reliability of the gridded data in representing instrumental records for the region. The analysis was restricted to the post-1931 period to ensure more reliable meteorological data coverage.

Analysis and Reconstruction Methods

Tree-ring width and climate relationships were analyzed with DendroClim 2002 software, using bootstrap confidence intervals for correlation significance. Correlations were computed for the period June of the previous year to August of the current year (accounting for cambial growth timing and prior-year effects).

Climate reconstruction methods follow standard dendrochronological procedures (Fritts 1976; Cook and Kairiukstis 1990). The reconstruction model – a transfer function – is typically a linear regression relating climate parameters to tree-ring indices. The procedure includes model calibration (using observed data), verification, and then actual reconstruction. Model reliability was assessed via split-sample tests, computing statistics: coefficient of determination (adjusted R^2), sign test (ST), reduction of error (RE), and coefficient of efficiency (CE) (Fritts 1976).

Regional representativeness was evaluated by correlating each reconstruction with the gridded PDSI field

over 1931–2016. The correlation maps indicate where each series reflects actual PDSI variability. Spectral analysis was conducted with the Multi-Taper Method (MTM), which effectively separates signal from noise in climate time series. We used 5 tapers (3π) and tested against a red-noise background at $p < 0.05$. Morlet wavelet transforms were applied to assess temporal changes in periodicities and phase relationships. Analyses were performed in R Studio and STATISTICA 12.

RESULTS

Tree-ring chronologies and Climate Response

Statistical characteristics of the indexed chronologies are shown in Table 1. All chronologies are suitable for dendroclimatic analysis: R_{bar} ranges from 0.45 to 0.74, and MS from 0.24 to 0.48, with the highest sensitivity at HEC (driest site) and lowest at BRG (wettest site; see Fig. 1).

The results of the correlation analysis show that precipitation plays an important role in controlling tree-ring width, particularly moisture accumulated in the soil during the second half of the previous growing season (Fig. 2). Precipitation in the current year was also significant for all chronologies during specific summer months. For BRG, located near the shore of Lake Baikal, significant relationships were found with January precipitation (snow) and warm conditions in October of the previous year. This likely reflects the influence of the lake-modified microclimate of Baikal (Mizandrontseva 1985).

Air temperature at the southernmost site (HEC, northwestern Mongolia) showed predominantly negative relationships with radial growth, which likely reflects an indirect moisture-mediated effect: under semiarid conditions, higher temperatures enhance evapotranspiration and intensify soil moisture deficit, thereby constraining tree growth (Liu et al. 2019). All chronologies showed significant positive correlations with PDSI, with the highest coefficients observed for BRG. Overall, the strongest correlations for all chronologies were observed in May–June.

PDSI Reconstruction and Validation

Based on the TRI – climate relationships, we selected the current-year mean May–July PDSI for reconstruction.

Table 1. Statistical characteristics of chronologies

Parameter	BRG	KST	KRN	HEC
Tree samples	33	74	118	20
Tree species	PISY, LASI	PISY	PISY	LASI
Period, year	1541–2019	1498–2016 (1699–1998*)	1608–2017 (1797–2017)*	1574–2018
Duration	479	519	410	445
R_{bar}	0.45	0.74	0.64	0.70
MS	0.24	0.35	0.34	0.48
SD	0.31	0.61	0.41	0.51
EPS > 0.85	1688–2019	1530–2016	1631–2017	1763–2018

*The range of the initial chronology of KST and KRN.

²<https://climexp.knmi.nl/>

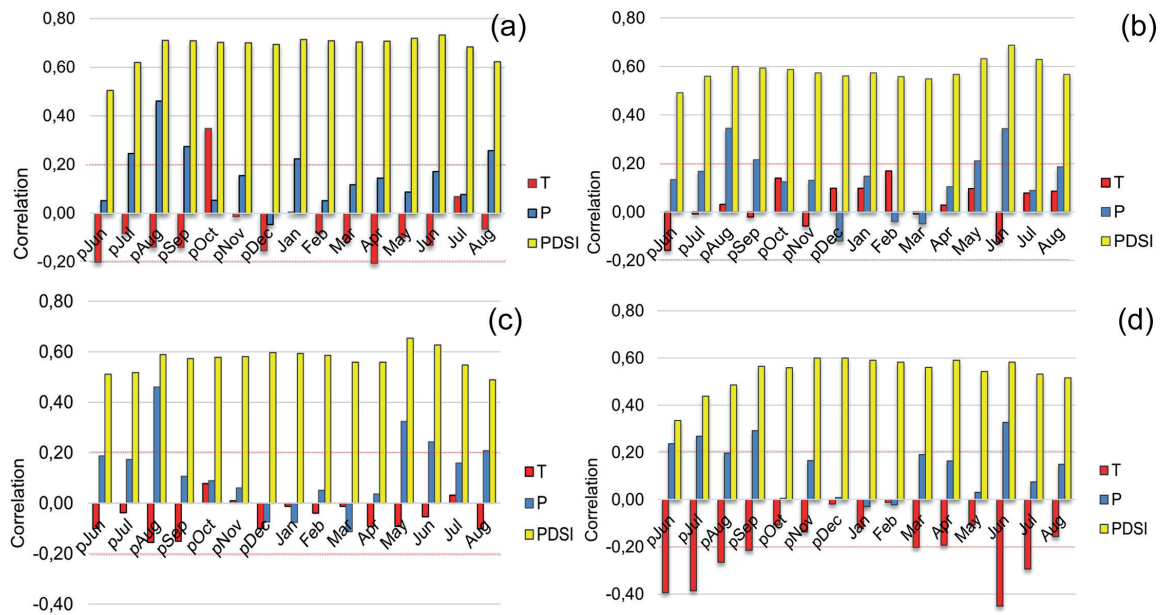


Fig. 2. Correlation of tree-ring chronologies: (a) BRG, (b) KST, (c) KRN, and (d) HEC with average monthly air temperature (T), precipitation amount (P) and PDSI for the period 1931–2016. Dotted red lines indicate the level of statistical significance ($p < 0.05$)

Model performance was evaluated by comparing observed and modeled PDSI using adjusted R^2 (Table 2). To assess predictive skill, the instrumental period was divided into two equal sub-periods for calibration and verification. Sub-period cross-validation demonstrated the stability of the regression models. The Sign Test (ST) indicated a significant excess of agreements, confirming that tree-ring variability captured PDSI variability. The positive values of the RE and CE statistics for all verification periods indicate that the reconstructions exhibit significant predictive skill. Overall, the models performed well: BRG explains 57% of

the variance in PDSI, KST 46%, KRN 37%, and HEC 34% for 1931–2016. The linear regression equations relating TRI to instrumental PDSI over the full instrumental period are as follows (Eqs. 1–4):

$$PDSI_{BRG} = 12.51 \times TRI - 11.81 \quad (1)$$

$$PDSI_{KST} = 5.33 \times TRI - 4.51 \quad (2)$$

$$PDSI_{KRN} = 4.95 \times TRI - 4.44 \quad (3)$$

$$PDSI_{HEC} = 3.22 \times TRI - 3.85 \quad (4)$$

Table 2. Statistics of split calibration and verification models for reconstructing the average PDSI value from May to July according to tree-ring chronologies

Calibration		Verification			
Period	R^2_{adj}	Period	ST	RE	CE
BRG					
1931–1973	0.49	1974–2016	32+/11	0.70	0.49
1974–2016	0.49	1931–1973	36+/7-	0.75	0.48
1931–2016	0.57	1931–2016	67+/19-		
KST					
1931–1973	0.58	1974–2016	32+/11-	0.56	0.36
1974–2016	0.44	1931–1973	31+/12-	0.67	0.44
1931–2016	0.46	1931–2016	64+/22-		
KRN					
1931–1973	0.44	1974–2016	27+/16-	0.54	0.23
1974–2016	0.34	1931–1973	36+/7-	0.60	0.33
1931–2016	0.37	1931–2016	59+/27-		
HEC					
1931–1973	0.26	1974–2016	33+/10-	0.47	0.35
1974–2016	0.37	1931–1973	29+/14-	0.49	0.09
1931–2016	0.34	1931–2016	67+/19-		

Fig. 3a shows the reconstructed May–July PDSI series for all four sites. The series clearly reflect local moisture regime differences. In the northern region (BRG, KST), wetter phases dominate: mean PDSI values for the full reconstruction are 0.74 (BRG) and 0.82 (KST). In the central and southern basin (KRN, HEC), mean values are 0.53 and −0.66, indicating pronounced aridity, especially at HEC (NW Mongolia).

To examine long-term fluctuations, smoothed series were computed using 11- and 30-year moving averages (Figs. 3b, c). The 11-year smoothed series indicate shifts in synchrony: prior to the 1870s, moisture variations in the Russian and Mongolian sectors were mostly asynchronous; during ~1870–1980 in-phase and lagged phases alternated; after the 1980s, an asynchronous regime resumed (Fig. 3b). Notably, PDSI values converged in the late 20th century. The 30-year smoothed series (253 years long, EPS > 0.85 since 1763) show divergent trends: Uda and Chikoy basins (KST, KRN) show a drying trend (decreasing PDSI), while Barguzin and Ider (BRG, HEC) show a wetting trend (increasing PDSI). HEC, however, remains below zero (never surpassing its long-term mean) (Fig. 3c).

Spatial correlation patterns

Fig. 4 shows maps of correlations between each reconstruction and observed PDSI (CRU TS) for 1931–2016. All reconstructions exhibit significant positive correlations over broad areas, indicating good representativeness.

BRG has the largest area of correlation: high coefficients ($r \approx 0.3$ – 0.7 , $p < 0.05$) cover coastal Baikal, western Transbaikalia, and part of the Eastern Sayan. KST shows a strong correlation over Western Transbaikalia and parts of Eastern Transbaikalia. HEC correlates highly with grid cells across the Mongolian part of the Lake Baikal basin. The highest correlation for KRN is observed in the border areas of Russia and Mongolia. These results confirm that the reconstructions reliably capture spatial climate variability.

Extreme Dry and Wet Periods

The long reconstructions (EPS > 0.85; 250–480 years) enable identification of the most prolonged drought and pluvial periods in each part of the basin (Fig. 3a). Drought periods are sequences of years with negative PDSI, and wet periods are those with positive PDSI. In the Barguzin Valley (BRG), droughts were observed in 1797–1809 and 1977–1984 and a wet period in 1925–1942. In the Uda Basin (KST), two 8-year droughts occurred: 1730–1737 and 1838–1845 (the latter more severe, including the driest year, 1838); wet periods were 1740–1760, 1926–1943, 1983–2002. In the border part (KRN), a drought occurred in 1648–1655 (including extreme 1650), followed by droughts in 1728–1738, 1954–1961, 1977–1984, and a wet period in 1865–1887. In NW Mongolia (Ider Valley, HEC), a drought occurred in 1769–1792. The 19th century featured the longest droughts: 1808–1843 and 1847–1869, with the peak wet interval of the entire record occurring between these mega-droughts (1793–1807).

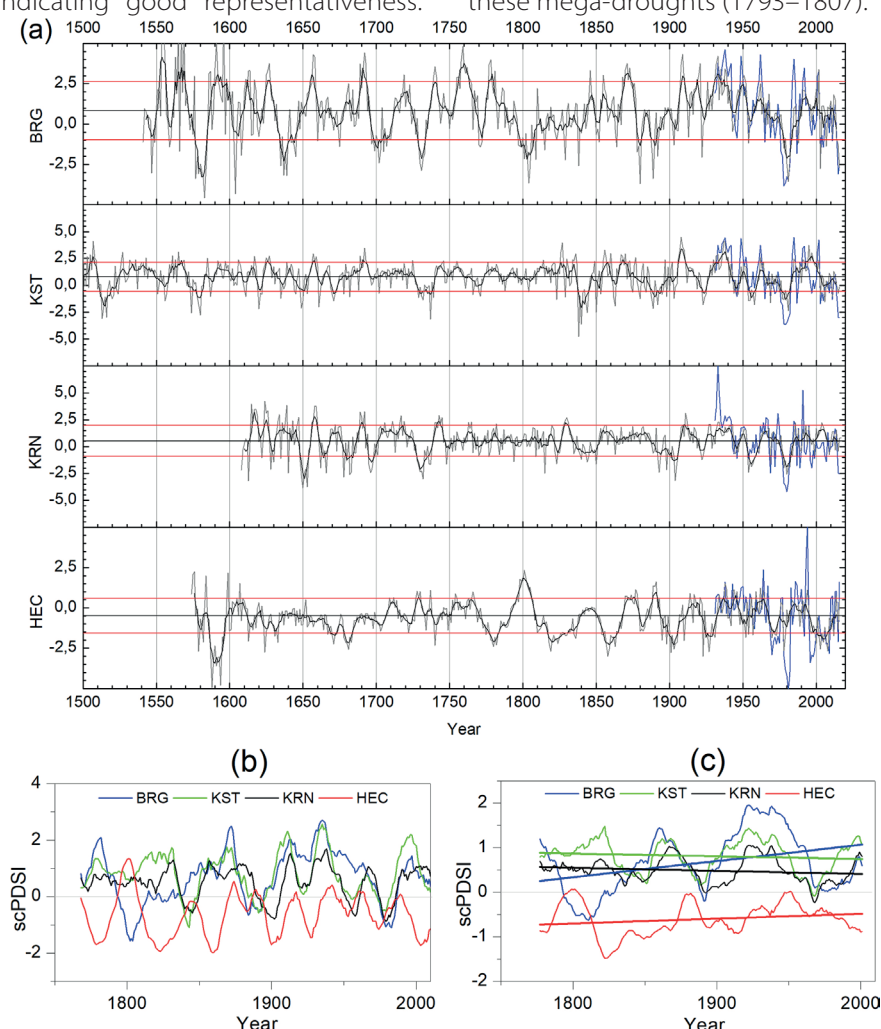


Fig. 3. Reconstruction of the average PDSI for May–July: (a) complete reconstruction for the four study sites (gray – reconstructed series; blue – instrumental data; black – 5-year moving average; red – ± 1 SD); (b) 11-year moving average; (c) 30-year moving average. Moving averages are shown for the common interval beginning in 1763, when EPS exceeded 0.85 for all chronologies

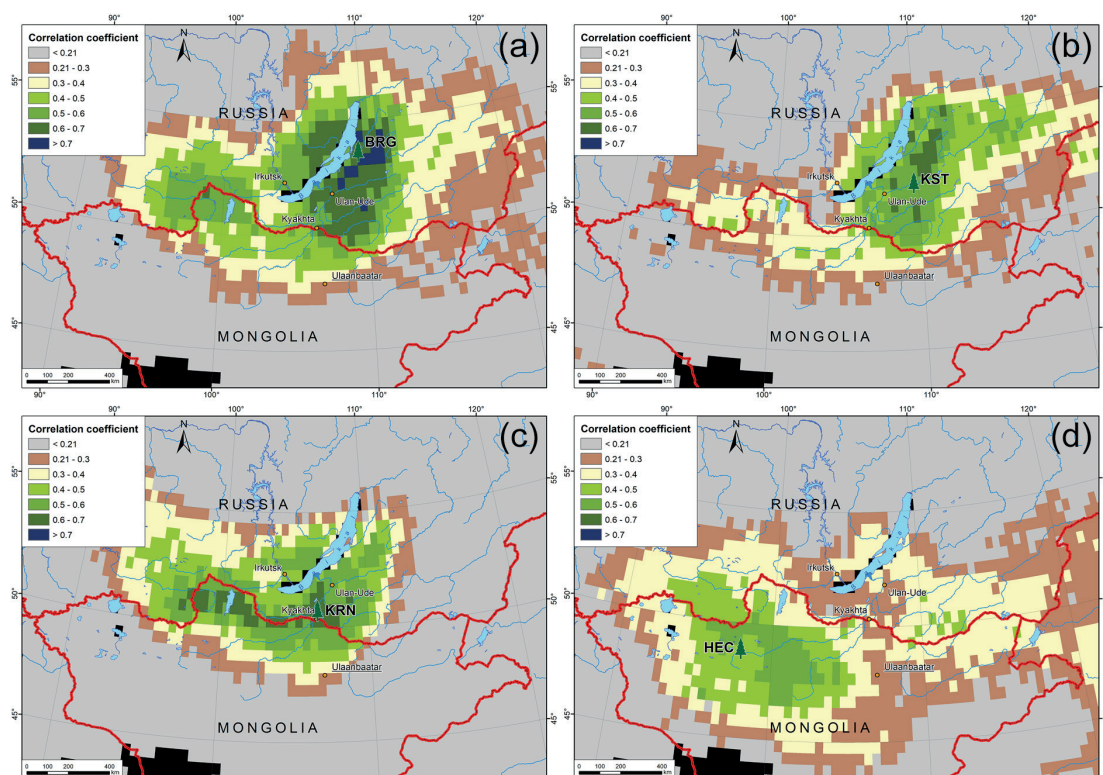


Fig. 4. Maps of spatial correlation between reconstructed and actual PDSI (1931–2016): (a) BRG, (b) KST, (c) KRN, and (d) HEC. The correlations are statistically significant at $r > 0.21$ ($p < 0.05$)

Extreme hydroclimatic events cause significant damage to ecosystems, agriculture, and economies, making their frequency important to understand. Extremely dry and wet years (below the 5th and above the 95th percentiles of PDSI) are listed in Table 3 for periods with $EPS > 0.85$. Some extremely dry and wet years affected broad areas across Baikal Asia – from the northern to the southern parts, as reflected in synchronous dry years (1863, 1923, 2003) and a synchronous wet year (1938). Our reconstructions and extremes align with previous studies. The negative extremes 1801, 1838, 1840 and the positive 1827–1830 coincide with Selenga River flow reconstructions (Andreev et al. 2001; Belokopytova et al. 2018; Demina et al. 2022). The HEC series (NW Mongolia) also matches prolonged drought and wet periods in west-central Mongolia (Davi et al. 2006) and certain common phases spanning central and eastern Mongolia (Pederson 2001; 2014; Davi et al. 2010; 2013). The late 18th–early 19th centuries exhibit spatial asynchrony: the central-western basin was wetter compared to the eastern basin (Davi et al. 2006). Our data confirm such out-of-phase regimes: during this period, the Mongolian part was anomalously wet, whereas the northern part of the basin experienced extreme droughts (1800–1805 period ranks among the driest years). In the modern era, a similar asynchrony is seen in the events of 1984, 2014 and 2016–2017 (based on the 10th and 90th percentile thresholds).

The reconstructed extreme years were compared with natural chronicles from Transbaikalia and Mongolia (Zadonina and Levi 2008) to validate the results for the pre-instrumental period, including asynchronous phases. The chronicles confirm, for example, the forest fires in the Barguzin Valley in 1804, and in the asynchronous year 1889 a severe drought occurred in Barguzin, while Cisbaikalia and eastern Transbaikalia simultaneously experienced flooding. Some events did not coincide, as chronicles more often describe regional-scale catastrophes rather than local ones.

During the recent asynchronous period of 2016–2017, the northern part experienced the largest forest-cover losses in 20 years due to wildfires, which were preceded

by spring-summer droughts (Tsydypov et al. 2022). In the same years, catastrophic floods caused by heavy rains were recorded in the northwestern and western aimags of Mongolia (Serdyanjiv et al. 2024). In Khovd, total annual and summer precipitation has decreased by ~20% over the past 40 years, yet extreme downpours have become more frequent. Among such anomalously wet years, the asynchronous year 1984 stands out, when up to 85% of the annual precipitation norm fell within a single season in some locations (Narangerel et al. 2025).

Spectral and Wavelet Characteristics

Fig. 5 shows power spectra and Morlet wavelet spectra for all four PDSI series ($p < 0.05$). High-frequency peaks appear in all series: BRG ~2.2–2.3 years; KST ~2–5 years; KRN ~2.2–2.6 years; HEC ~2.4–3.6 years. Low-frequency oscillations (multi-decadal) are most pronounced in KST and HEC. KST has persistent cycles of ~26–36, ~46.5, ~48.7 years; HEC has ~26.9–36.6, ~39.4, ~42.7, ~46.5, ~51.2, ~56.8 years. KRN shows significant power at ~14–17, ~23–27, ~33 years. These periods match the Pacific Decadal Oscillation (PDO) timescales (~20–30, 50–70 years). The ~14–17 year cycle in KRN is consistent with the ~18-year lunar nodal cycle.

Wavelet analysis confirmed the main intra-centennial periodicities identified by the MTM method. In addition to high-frequency oscillations, the BRG chronology exhibited a pronounced low-frequency cycle with a period of ~16–22 years. This periodicity is consistent with the Hale solar cycle and was particularly evident from the 1720s to the 1770s. A common ~26–48-year cycle was simultaneously observed in KST and HEC throughout approximately the 1800s–1950s. Of note, the power of the 50–60-year periodicities in KST is weakly expressed. In KRN, ~14–17-year cycles were recorded around 1650–1720, followed by dominant ~23–33-year oscillations in 1720–1750. An approximately 32-year common cycle was identified in both KST and HEC during 1920–1970.

Table 3. Extremely dry and wet years in the reconstructed PDSI

BRG		KST		KRN		HEC	
5P	95P	5P	95P	5P	95P	5P	95P
		1556, 1574, 1579–1580	1561, 1565				
	1689, 1692–1693	1620, 1649–1650 , 1661, 1671	1617, 1627, 1657, 1689 , 1692	1640, 1649–1651 , 1653, 1666 1678, 1682–1683, 1696–1697	1634, 1638–1639, 1643, 1647, 1657–1659 , 1689–1690 , 1692		
1702, 1730–1731	1740, 1758–1760, 1762, 1777–1778	1737	–	1730–1732	1711, 1717, 1719, 1743, 1745	1780	1798–1799
<u>1801, 1804–1805</u> , 1809, 1829, 1838, 1880, 1889	1871	1838 , 1840, 1843–1844, 1850, 1863 , 1888– 1889 , 1892	1826–1827, 1836, 1856, 1860, 1867, 1870	1815, 1893, 1898	1829–1830	1819, 1858–1859, 1863	<u>1800–1805</u> , <u>1889–1891</u>
1980–1982	1908–1909 , 1921, 1932–1933	1923, 1954–1955 , 1958, 1969, 1981	1907–1910 , 1932–1933 , 1937–1938 , 1995, 1997	1904, 1954 , 1980	1911–1912	1901, 1903, 1923 , 1927, 1978	1938–1939 , 1944, 1962
2003, 2016, 2019	–	2006	–	–	–	2003, 2008	–

Note: Synchronous dry or wet years are highlighted in bold; asynchronous years are marked with a dash.

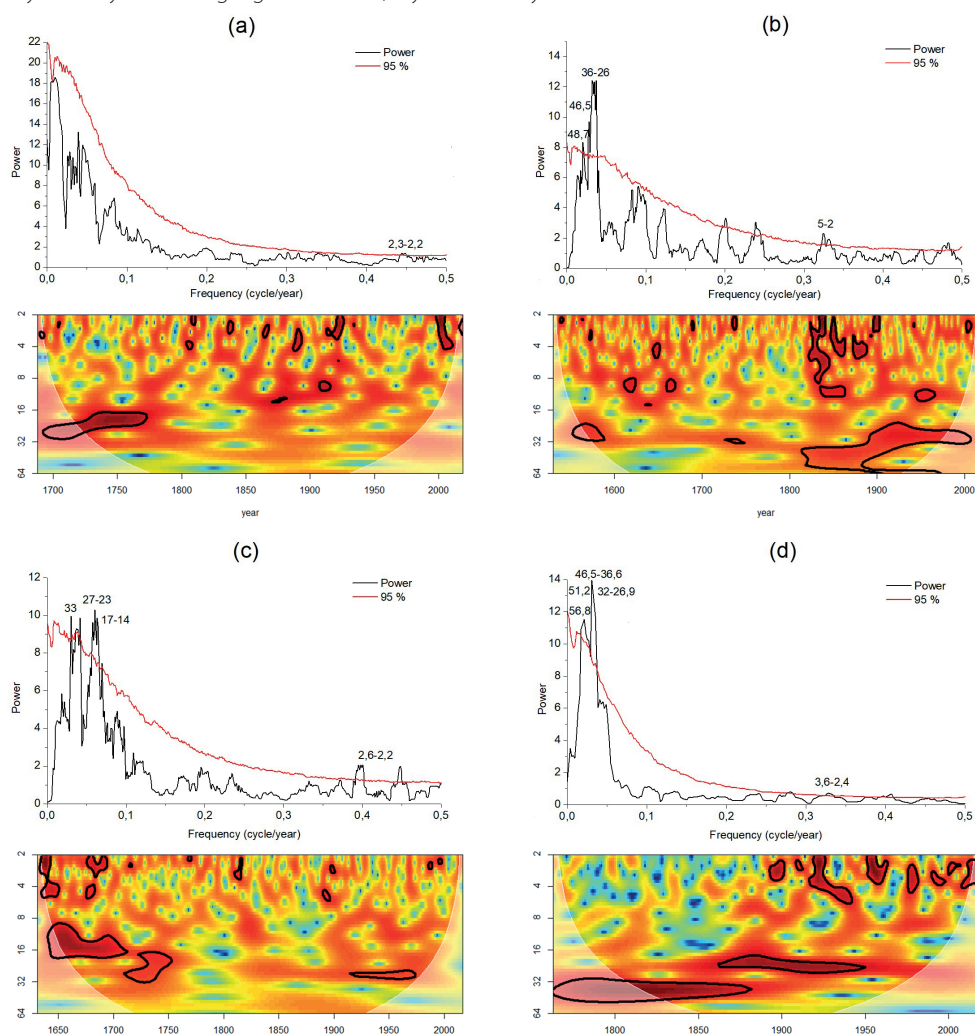


Fig. 5. Spectral power of the series: (a) BRG, (b) KST, (c) KRN, (d) HEC ($p < 0.05$) obtained by the multitaper method and their Morlet wavelets

Synchrony and Asynchrony Between Regions

Because the fluctuations can be both synchronous and asynchronous, we calculated running correlations for each pair of reconstructed PDSI series for 1763–2016 ($EPS > 0.85$ for the common interval), using 11- and 30-year windows with a 1-year step. Correlation values range from negative values (indicating antiphase) to positive values (indicating in-phase behavior). The results (Fig. 6) clearly illustrate the sequence of synchronous and asynchronous intervals over the past 253 years.

The 11-year running correlations (Fig. 6a) show that among the chronologies BRG, KST, and KRN (Russian part of the basin), positive relationships dominate, with only occasional negative episodes. Between the Russian and the Mongolian PDSI series, phases of synchrony and antiphase regularly alternate; correlation coefficients vary approximately from -0.8 to 0.8 (Fig. 6b).

In the 30-year window, the synchrony among the Russian PDSI series strengthens during the 20th century, especially between BRG and KRN (Fig. 6a). Correlations between the Russian and the Mongolian series, which were predominantly negative until the late 19th century, shift toward positive values by the mid-20th century: in the second half of the 20th century, all chronologies demonstrate persistent in-phase behavior (Fig. 6b).

Cross-wavelet analysis of the series (Fig. 7) reveals coherent variations across multiple temporal scales. For pairs of Russian part chronologies, the phases of oscillations within the significant regions of the spectrum predominantly coincide (arrows $\rightarrow$), or one series slightly leads the other by $\pi/2$ ($\nearrow/\searrow$) (Fig. 7a). It was found that in the KST, KRN, and HEC PDSI reconstruction series, persistent low-frequency (multidecadal) oscillations are present throughout the entire interval, with phase arrows transitioning from antiphase through intermediate phase shifts to in-phase behavior and then back to antiphase (with some episodes falling outside the cone of influence). High-frequency (interannual) coherence between the Russian and Mongolian series appears only from the late 19th century onward (Fig. 7b).

Between the BRG and HEC series, in-phase oscillations are detected only during ~ 1860 – 1880 (with a ~ 22 -year cycle); in subsequent years, low-frequency coherence is absent. The presence of a common ~ 32 -year cycle allows it to be linked to the Pacific Decadal Oscillation previously documented for the Russian (Demina et al. 2017) and Mongolian (Davi et al. 2010) sub-basins. The absence of pronounced low-frequency variations in the Barguzin chronology is likely explained by the orographic isolation of Lake Baikal, which is shielded from the west and east by mountain ranges that block the intrusion of near-surface Pacific and Atlantic air masses (Mizandrontseva 1985).

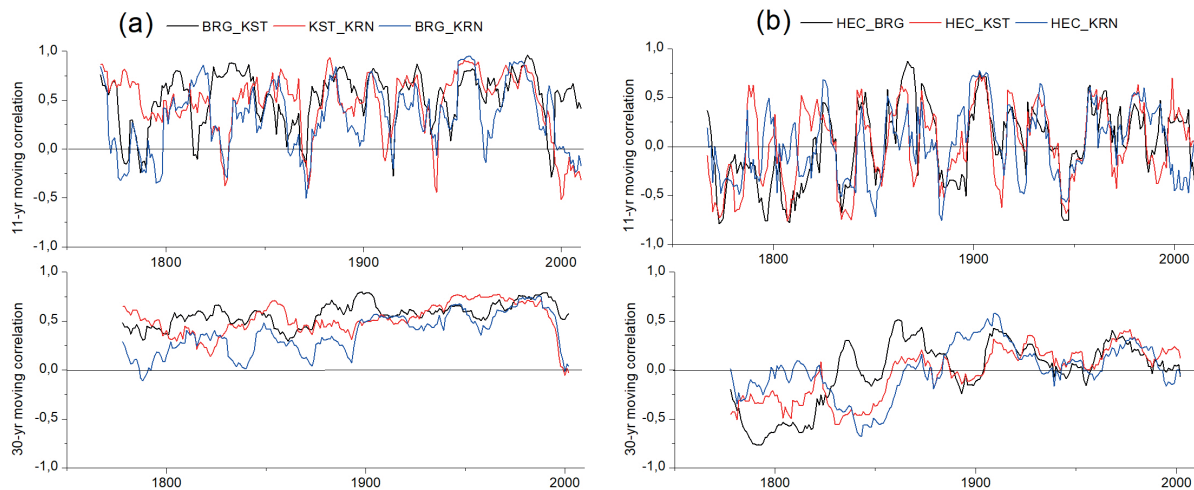


Fig. 6. Running correlations between reconstructed PDSI series calculated using 11- and 30-year moving windows: (a) among the Russian series; (b) between the Mongolian and Russian series

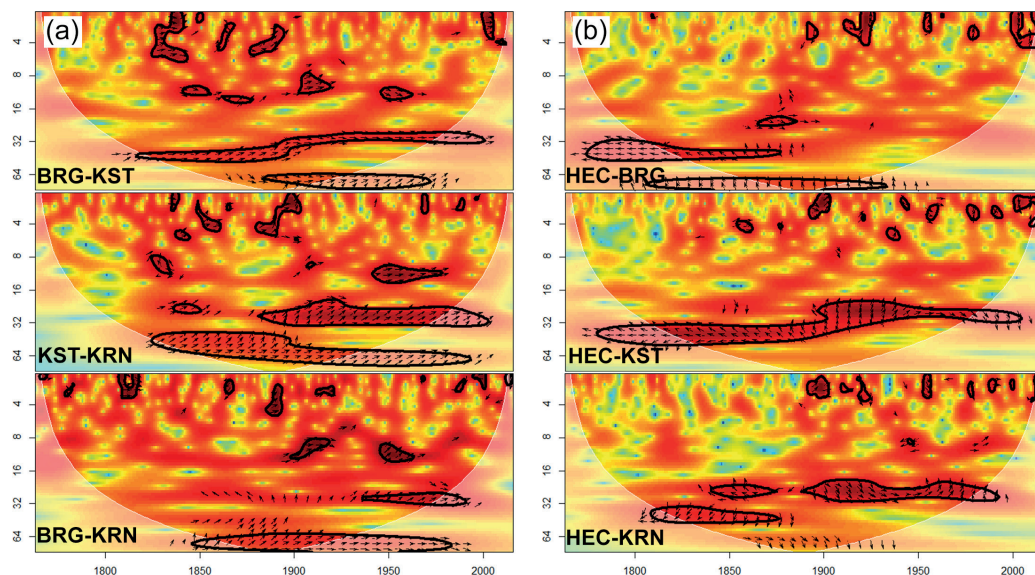


Fig. 7. Cross-wavelet of reconstructed PDSI series for the period 1763–2016, arrows ($\rightarrow$ – in phase, $\leftarrow$ – out of phase, $\nearrow/\searrow$ – advance/delay), the white line indicates the cone of influence: (a) between the PDSI series of the Russian part of the basin, and (b) between the PDSI series of the Mongolian part of the basin and the Russian part

DISCUSSION

The results show that the chronologies from the Russian territory are periodically synchronous and asynchronous with those from northwestern Mongolia, reflecting the influence of both local orographic factors and large-scale atmospheric processes of southern Siberia (Voropay and Ryazanova 2023). Local blocking anticyclones over eastern Siberia and the Mongolian Plateau play a significant role in shaping the precipitation regime (Antokhina et al. 2019; 2023).

Mean values of the reconstructed PDSI demonstrate a climatic gradient from the humid north to the semi-arid south. The 11-year smoothed PDSI values indicate similar climatic conditions during the second half of the 20th century in the valleys of the Uda, Chikoy, and Ider rivers. Long-term 30-year trends (1763–2016) show decreasing moisture availability (increasing aridity) in the Uda and Chikoy valleys and increasing moisture availability in the Barguzin and Ider basins. These findings are consistent with reconstructions of multidecadal streamflow variability of the lower Selenga (Andreev et al. 2001; Belokopytova et al. 2018) and its upper reaches (Davi et al. 2006). Recent hydrological studies from the Selenga basin also indicate spatially heterogeneous runoff changes under recent warming (Frolova et al. 2017). Notably, modern droughts in Mongolia, although extreme, are not unprecedented within the multi-millennial context of climate reconstructions for Central Asia (Hessl et al. 2018).

These regional trends align with global aridification dynamics. According to Sardans et al. (2024), between 1960 and 2023 approximately 28% of global land areas became drier, while ~20.5% became wetter. In the study by Gelfan et al. (2021), for the period 1976–2016 compared with 1950–1975, the streamflow regime of rivers flowing into Baikal changed: discharge increased in the northern tributaries of the lake (from the Turka River and northward), as well as in the upper Selenga tributaries (the Selenga and Delgermuren rivers), whereas discharge decreased in the lower tributaries (Uda, Chikoy, Khilok rivers). Our reconstructions are broadly consistent with these patterns.

The observed strengthening of synchrony among the Baikal basin tree-ring series is consistent with the global trend of increasing tree-growth synchrony, attributed to the intensification of shared climatic influences (Shestakova et al. 2016; Wang et al. 2021; Li et al. 2024). In particular, synchrony tends to increase in regions with pronounced moisture deficit, where drought is the primary limiting factor of growth (Gazol et al. 2020; Tejedor et al. 2020), whereas in the Mediterranean region, severe droughts

instead lead to desynchronization of growth (Sangüesa-Barreda et al. 2019). Despite the increase in regional (a) synchrony, substantial spatial heterogeneity persists. This heterogeneity manifests in high-frequency growth fluctuations and is driven by local site conditions and species composition (Shestakova et al. 2019; Dolgova et al. 2019), which may reduce synchrony and modify growth sensitivity (Muffler et al. 2020).

A comparison of tree-ring data from adjacent regions of the Pacific coast reveals coherence of climatic fluctuations at multidecadal scales (Fang et al. 2018). Results of spectral and wavelet analyses show common low-frequency (~32-year) PDSI oscillations in the tributary basins of the Selenga River, indicating the influence of Pacific processes even on remote inland territories. The detected 14–17-year cyclicity in the border region of the study area corresponds to ~18-year lunar nodal cycles documented in the Minusinsk Basin and on the Mongolian Plateau (Demina et al. 2022; Davi et al. 2010). Thus, the microclimate of the Baikal basin responds sensitively to both local factors and global atmospheric processes. Tree-ring chronologies confirm their value as indicators of large-scale climatic phenomena.

Modern warming driven by increasing greenhouse gas concentrations, together with variability in Pacific and Atlantic ocean-atmosphere systems, may substantially influence future drought dynamics in Inner Asia (Dai 2021; Davi et al. 2010; Wang et al. 2022).

CONCLUSION

In this paper, we reconstructed multi-century changes of the Palmer Drought Severity Index for the transboundary territory of the Lake Baikal basin, reflecting both local climates and connections to large-scale atmospheric processes. A drought tendency was identified for the central-southern territories (KST, KRN) in the basins of the Uda and Chikoy rivers, whereas the opposite trend, i.e., increasing moisture availability, is observed in the northern part (BRG) and in northwestern Mongolia (HEC), in the basins of the Barguzin and Ider rivers.

Promising avenues for future research include analyzing the spatial synchrony and asynchrony of climatic signals in other parts of the Lake Baikal basin and examining the teleconnection mechanisms driving these differences across multiple temporal scales. This will provide a stronger basis for understanding drought and moisture dynamics in the Lake Baikal basin, which contains the world's largest reservoir of liquid freshwater and is experiencing warming faster than the global average. ■

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SOIL-CRYOGENIC COMPLEXES OF WEST SIBERIAN TUNDRA

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ABSTRACT. Soil-cryogenic complexes (the system of “permafrost-affected soils – upper permafrost”), located at the interaction hotspot of the biosphere and the cryosphere, were studied at five key sites in Northwestern Siberia situated on geomorphological terraces of different origin – from marine to fluvial and lacustrine – and age (Late Pleistocene and Holocene). In the context of the present-day permafrost zone transformation under global climate change and local anthropogenic impact, they are of considerable ecosystem significance. Based on the geomorphological and cryolithological studies, it was concluded that fully developed soil-cryogenic complexes (SCCs), comprising the active layer (AL), transient layer (TL), and intermediate layer (IL), are spatially limited in the study area due to lithogenic and ecosystem factors. Due to the wide distribution of deeply thawing sandy, ice-poor sediments where continuous and thick vegetation cover is unable to develop, morphologically expressed TL was absent, having already fully thawed. Modern soil formation most often occurs directly above the degrading IL or even Late Pleistocene frozen sediments containing fragments of ground ice. Relatively stable permafrost conditions and full-profile SCCs were observed in the thick peat massifs only where the presence of thick organic horizons reduces the heat flux and limits the active layer thickness (ALT). Furthermore, a number of hazardous geomorphological cryogenic processes – including thaw ground subsidence, thermal denudation, and thermal abrasion in coastal areas – contribute to the degradation of SCCs, thereby diminishing their protective role in permafrost preservation. A comprehensive approach to the assessment and forecasting of the ecological state and dynamics of fragile Arctic ecosystems, based on SCC research, could provide a deeper understanding of both natural and anthropogenic processes.

KEYWORDS: permafrost-affected soils, soil-permafrost coevolution, cryostructures, transient layer, intermediate layer, Arctic

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INTRODUCTION

Nowadays, the Russian Arctic is one of the most promising regions, where major governmental projects are being implemented. The most dynamically developing region here (not only in Russia but in the global Arctic) is the northern part of West Siberia (Cordier et al. 2025), which is administratively part of the Yamal-Nenets Autonomous Okrug. Firstly, the active exploration of this territory in the 20th–21st centuries is linked to its high mineral resource potential: more than 130 hydrocarbon fields are located there (Khimenkov et al. 2020). Secondly, the ice navigation regime of the Arctic seas has changed during the last few decades and has significantly prolonged the period of the Northern Sea Route availability for the cargo sea transportation from Asian countries to Russia and Europe. The most important terrestrial aim, consequently, is the development of transport and economic infrastructure along this route to provide fast and safe transportation.

Thirdly, there are several initiatives of the local authorities to improve citizens' living comfort, including increasing the transport availability of its remote regions. Anthropogenic activity on these territories, a major part of which is located in the permafrost zone, comprehensively influences the regional environment, especially permafrost conditions and terrestrial ecosystems. This influence mostly impacts the system of “permafrost-affected soils – upper horizons of permafrost” located in the interaction hotspot of the biosphere and cryosphere, and responds to changes in both of them.

Lupachev and Gubin (2023) proposed considering modern permafrost-affected soils and the upper permafrost horizons as the unified system – the soil-cryogenic complex (SCC). The SCC includes three main structural elements: a modern soil profile (mostly limited by the active layer thickness (ALT)), the transient layer (TL), and the intermediate layer (IL) of permafrost. TL and IL are characterized by specific ice-rich cryogenic structures – ataxitic, lenticular, layered, etc.,

as well as pure ice inclusions (Shur 1988). The SCC structural elements are relict formations of the earlier warmer periods of the Holocene in the permafrost zone of the Arctic and subarctic (Shur 1988; Shur et al. 2005; Bockheim, Hinkel 2005). They thaw at different frequencies; therefore, they could be incorporated into the soil formation sphere and biogeochemical cycles, and accumulate various soil formation products – soil organic matter (SOM), pedogenic metal oxides, soluble substances, etc. TL formed as a result of the recent average ALT dynamics (Shur 1988); its ice-rich cryostrucures may have derived from ice segregation at the base of the active layer. IL has been inherited from the Holocene climatic optimum (Shur 1988) – the Early to Mid-Holocene warm period that ended around 5–4 ka (Borisova 2014). This layer could also be enriched with ice due to the gradual decrease of the ALT from the Mid to Late Holocene.

Pedogenesis was permanent throughout the Holocene in a major part of Northwestern Siberia; thus, the interaction between soils and underlying permafrost was constant. The Holocene climatic optimum is associated with significant air temperature increase (up to 12–14°C higher than the late glacial maximum, and 2–4°C higher than modern values), a series of synchronous tundra-taiga borderline shifts (Khotinskiy 1977; Borisova 2014), and different-scale Kara Sea level fluctuations (Fotiev 2005). The highest Holocene sea level rise occurred during the Boreal period, reaching 8–10 m (up to 12 m) above the modern level, corresponding to the geomorphological levels of the floodplain complex and the first terrace. During this period, pedogenesis was replaced by marine sedimentation. Atlantic and Sub-Atlantic periods were associated with less pronounced sea level rises, and during the Sub-Atlantic period, starting 4–3 ka, the 1–3°C cooling caused the tundra-taiga borderline retreat southwards to the Polar Circle (Vasil'chuk et al. 1983). Thus, alternation of warming and cooling stages and associated environmental shifts in Northwestern Siberia during the Holocene led to significant variations in the ALT in the past. However, according to Fotiev (2005), the total degradation of the upper permafrost layers did not happen there even in the Holocene climatic optimum.

In the context of permafrost zone transformation under global climate change and local anthropogenic impact, SCC is of considerable ecosystem significance. Firstly, thawing of the ice-rich TL and IL can trigger hazardous processes (thermokarst, thermal erosion, etc.) that negatively affect infrastructure stability and constrain the feasibility of engineering exploration of these territories (Shur 1988; Kanevskiy et al. 2014). Secondly, along with biochemical decomposition of SOM contained in permafrost, greenhouse gas emissions (CO_2 , CH_4 , NO_x , etc.) into the atmosphere may increase as a result of permafrost thawing (Shur et al. 2005; Ping et al. 2015; Oblogov et al. 2020). Thirdly, TL and IL thawing can activate geochemical fluxes in ecosystems. In the modern industrial era, uppermost permafrost horizons can be contaminated by accumulated anthropogenic pollutants migrating in soils as a result of local pollution or long-distance atmospheric transport (Lupachev et al. 2022; Gulfam-E-Jannat et al. 2025). Soluble ions, biogenic (metal-organic compounds, bioavailable element forms, soluble phosphates) and potentially toxic (heavy metals, anthropogenic hydrocarbons, pesticides, radionuclides, etc.) matters can be released from the thawing permafrost and then influence the biogeochemical cycles in adjacent ecosystems (Ji et al. 2019; O'Donnell et al. 2024). Disruption of the matter balance in terrestrial and aquatic ecosystems could irreversibly impact their functioning, potentially

leading to ecosystem collapse. It is also important to mention that permafrost degradation always affects the traditional living and land use practices of the Arctic indigenous communities – reindeer herders, hunters and fishermen, – due to changing commercial animal resources ecology and traditional animal migration routes (Allard et al. 2023).

A comprehensive approach to the evaluation and forecasting perspectives of the ecological state and dynamics of cryogenic processes of the fragile Arctic ecosystems, based on SCC research, could provide a deeper understanding of natural and anthropogenic processes. However, data on the structure and current state of SCCs across different permafrost regions remain sparse. Systematic studies of SCC in the Russian Arctic have been carried out only in two regions – the Kolyma lowland, Northeastern Yakutia (Lupachev, Gubin 2008, 2023), and in the South-East of Bolshezemelskaya tundra near Vorkuta, northeastern European Russia (Kaverin et al. 2012). Few studies of SCC are known for the North American Arctic – North Slope region, Northern Alaska, and Yukon River Valley, Central Alaska, and the Canadian Northwest Territories (Bockheim, Hinkel 2005; Ping et al. 2013; 2015). In tundra environments of Northwestern Siberia, SCCs remain unstudied, and data on soil and geocryological research become obsolete.

The variety of ecological functions of SCC and its close connection with other cryogenic ecosystem compartments, especially under conditions of thin annual ALT, is the reason why SCC study is an important problem for the Russian Federation as the state where 2/3 of the territory is underlain by permafrost. Beyond their fundamental scientific value, spatial permafrost research in different regions is of the great social and economic significance as part of the “Basis for the Russian Federation government policies in the Arctic until 2035”¹. Thus, comprehensive characterization of modern SCCs and projection of their probable development trajectories and associated ecosystem consequences represent pressing research objectives.

MATERIALS AND METHODS

The study area

Northwestern Siberia (Fig. 1) is located in the Arctic climate zone; mean annual air temperatures (MAAT) here vary from –4.5 to –10.4°C, and mean annual atmospheric precipitation (MAAP) varies between 250 and 600 mm/yr (Table 1). During the last few decades, the positive climate trend was observed: MAAT increased by 2.8°C for the period of 1970–2020 (0.56°C per decade), accompanied by a 5–10% annual increase in MAAP (Vasiliev et al. 2020). Long-term temperature monitoring indicates a gradual increase in permafrost temperature. From 1970 to 2020 (Vasiliev et al. 2020) it increased at average rates: 0.056°C/yr in typical tundra, 0.04–0.05°C/yr in southern tundra, and 0.035°C/yr in northern boreal forests. Since 2007, mean annual temperatures of the active layer have become positive; thus, the active phase of permafrost degradation has started. ALT deepening, which leads to the thawing of ice-rich permafrost layers, affects all landscape subzones of Western Siberia (Vasiliev et al. 2020; 2024). Consequences of the permafrost thawing in tundra zones are not so catastrophic yet. However, significant intensification of destructive cryogenic processes, associated with ice-rich permafrost degradation, is predicted for the 2030–2050 period (Kislov et al. 2023).

¹The Decree of the Russian Federation President No. 164 (dated March 5, 2020) on the “Basis for the Russian Federation government policies in the Arctic until 2035”. Kremlin, Russia. 2020. (in Russian).

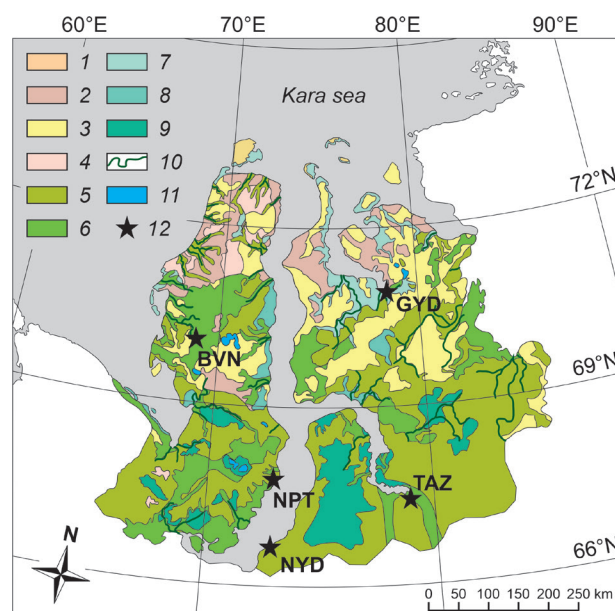


Fig. 1. Tundra environments of the permafrost zone in Northwestern Siberia (based on²): 1 – Rush/grass, forb cryptogram (moist); 2 – Graminoid prostrate dwarf-shrub, forb (moist to dry); 3 – Nontussock sedge, dwarf-shrub, moss (moist); 4 – Prostrate dwarf-shrub, herb (dry); 5 – Erect dwarf-shrub (dry); 6 – Low-shrub (dry); 7 – Sedge/grass moss (wet); 8 – Sedge, moss, dwarf-shrub (wet); 9 – Sedge, moss, low-shrub (wet); 10 – Riparian corridors; 11 – Lakes; 12 – Key sites: BVN – Bovanenkovo; NYD – Nyda; NPT – Novy Port; TAZ – Tazovsky; GYD – Gyda

Key sites were located on geomorphological terraces of different origin – from marine to fluvial and lacustrine ones. These terraces are of Late Pleistocene and Holocene age (Table 1). TAZ, BVN, and GYD sites were situated in the typical tundra subzone; NPT and NYD – in the southern tundra subzone. Two landscape subzones differ in permafrost conditions: in typical tundra permafrost is distributed continuously and mean annual ground temperature (MAGT) ranges from -2 to -6 °C, and in southern tundra it is located discontinuously and MAGT varies between -1.3 and -4.7 °C (Table 1). ALTs differ significantly between subzones and within key sites in different-textured soils. Various cryogenic processes are widespread across the study area – thermal abrasion, thermal erosion, thermokarst, frost heaving, frost cracking, etc.

Local interactions of lithological, geomorphological, and hydrothermal conditions explain variations in thawing depth of permafrost-affected soils (WRB 2022): Cryosols have an annual thaw depth of up to 100 cm, and Gleysols and Podzols are characterized by 100–150 cm ALT. Sandy Arenosols, commonly developed in well-drained ecosystems with discontinuous or totally absent vegetation cover (e.g. non-vegetated hill shoulders or watersheds with aeolian deflation hollows), thaw annually to depths of several meters. In some cases, there are taliks developed under low-lying sandy floodplains. Histosols are also widely distributed on key sites. They are mostly characterized by the lowest ALT, which has not demonstrated significant deepening during the last few years (Khomutov et al. 2024).

Methods

SCCs were studied in natural outcrops and drilling boreholes. Drilling was carried out using a motor-holster Hüter GGD-52 and a 59-mm diameter core sampler. Soil profiles were described according to the WRB Soil Taxonomic System (2022). The cryogenic structure of permafrost cores was classified according to (Kanevskiy et al. 2014). Soil pits and boreholes were made during field seasons 2023–2025; from late August to late October, when the observed ALT was closest to its maximum annual depth.

²CAVM Team (2003). Circumpolar Arctic Vegetation Map. Scale 1:7,500,000. Conservation of Arctic Flora and Fauna (CAFF) Map No. 1. U.S. Fish and Wildlife Service, Anchorage, Alaska.

RESULTS

NYD key site

Soils at the NYD key site included Gleyic Turbic Cryosols and Gelic Gleysols. They developed in silty and clayey lacustrine loams overlying a thick alluvial sandy layer in the structure of a gentle slope of a fluvial-lacustrine terrace. Fine particles of plant residues occurred buried during cryoturbation in Cryosol profiles (Fig. 2 – sections BVN-24-03/04/08, GYD-25-01/03/05). The territory of this key site was previously affected by solifluction. Signs of lateral matter redistribution along slopes were especially obvious at hilltops. These terrain positions were not influenced by peripheral thawing, so ALT was minimal there and did not exceed 90 cm. A well-expressed system of TL and IL was observed there. Its total thickness was between 32 and 47 cm in silty loam soils. TL and IL were characterized by greater ice content in loamy Gleysol profiles because of the finer sediment textures and flatter mesorelief that determine wetter and colder local hydrothermal conditions. For that reason, more ice segregated at the bottom of the AL.

Upper permafrost horizons included several layers with various cryogenic structures from reticulate to lenticular and porphyritic, i.e., with ataxitic sublayers. Among the pedogenic features observed in upper permafrost horizons, oxidized Fe³⁺ neoformations were visually distinct. They were associated with core sections of maximal ice content and were located at the contact between the mineral matrix and ice inclusions. There were no signs of gleyic metamorphism in permafrost in comparison with modern soils within AL. In the upper parts of hillslopes where the peripheral thawing influence was significant, TL and IL were absent in the SCC. It is likely that they have been completely thawed in recent years.

NPT key site

Soils at the NPT key site were classified as Arenosols, developed on sandy deposits subject to active aeolian redistribution of mineral material. Organic horizons

Table 1. Natural factors of tundra environments at studied key sites in Northwestern Siberia

Factor	Parameter		NYD	NPT	BVN	TAZ	GYD
Climate	MAAT, °C ¹		−4.5	−7.1	−6.7	−7.3	−10.4
	MAAP, mm ¹		379	263	328	577	309
Permafrost	Distribution		Discontinuous		Continuous		
	MAGT, °C		−2.2/−1.9 ²	−3.9/−1.3 ²	−6.0/−3.0 ³	−3.5/−2.0 ³	−6.0/−5.0 ⁴
	Mean ALT, cm	Sand	187 ²	164 ²	105 ³	137 ³	128 ³
		Loam	120 ²	57 ²	70 ³	58 ³	65 ³
		Peat	43 ²	35 ²	43 ³	47 ³	46 ³
	Cryogenic processes		Deflation, solifluction	Thermal abrasion, thermal erosion, frost cracking, deflation	Thermal denudation, thermokarst, thermal erosion, frost cracking, frost heaving, deflation, solifluction	Thermokarst, thermal erosion, frost heaving, frost cracking, deflation	Thermal abrasion, thermokarst, solifluction, frost heaving
Geomorphology	Terrain forms		Terraces				
	Genesis		Fluvial-lacustrine	Fluvial	Marine	Fluvial Fluvial-lacustrine	Marine, Fluvial-marine Fluvial-lacustrine
	Age	Late Neopleistocene	Upper Neopleistocene-Holocene	Upper Neopleistocene		Upper Neopleistocene-Holocene	
		Ermakovo	Sartan	Ermakovo	Kargin	Kargin – Sartan	

Notes: ¹ – data from³ (Bulygina et al. 2025); ² – data from; ³ – data from⁴ (Khomutov et al. 2024); ⁴ – data from (Obu et al. 2019).

of such soils were thin (less than 5 cm) and poorly decomposed (Fig. 2 – sections NYD). Immobilization and crystallization of Fe compounds in the suprapermfrost soil horizons were, probably, connected to the presence of a contrasting mechanical barrier at 50–60 cm depth. It was well-expressed visually in soils on fluvial terraces. There were layers of alluvial and aeolian sand that gave way to bluish-gray marine clay at this depth, and the AL bottom often matches this lithological contact. On a modern floodplain, where there was no such contact observed, the Arenosol profile differed poorly horizontally by texture and morphological reflections of mineral mass pedogenic metamorphism degree.

At depths of 115–140 cm in SCC profiles on the fluvial terrace, the ice-rich permafrost layers were observed. They were characterized by lenticular cryogenic structures. Their thickness varied between 20 and 35 cm, and it decreased along as it got closer to the slope's shoulder. In the underlying permafrost horizons, cryogenic textures were massive and, less commonly, thin-layered. No gleyic or oxic Fe metamorphism was observed along the clayey layer cores, and their bluish-gray color is, most likely, the original.

TAZ key site

Soils at the TAZ key site were represented by two deeply thawed (down to 150 cm) Arenosol profiles, and

one far shallower thawed Histic Cryosol. Arenosols were characterized by thin (2–3 cm) organic horizons with a low plant residue decomposition degree. Histic Cryosols, oppositely, differ in low ALT (66 cm) despite the same texture due to the 30-cm thick organic horizon that limits thawing (Fig. 2 – section TAZ-24-02). The mineral part of soil profiles did not include visually well-expressed Fe neoformations, except thin so-called pseudo-fibers. Their formation is associated with gradual soil thawing and suprapermfrost oxidized groundwaters standing during the spring season. Cryoturbation process signs, such as irregular horizon boundaries, buried plant residues, and frost boil microrelief of the surface, were widely distributed across different terrain forms at the TAZ key site.

Upper permafrost in deeply thawed SCC had low ice content and massive cryogenic structures. Ice-rich layers, even if they existed, probably had thawed completely in recent years (Fig. 2 – TAZ-24-01, 25-01 sections). Despite the same mineral soil texture, in SCC on low lacustrine terraces the ice-rich TL and IL still remain due to the heat-insulating role of thick organic horizons (Fig. 2 – TAZ-24-02 section). Upper permafrost layers were of the braided cryogenic structure; the thickness of ice inclusions varied from 3 to 5–6 cm, and the distance between them was 4–7 cm. In contact with the mineral matrix and ice inclusions, the oxidized Fe concretions were observed, despite the fact that the main matrix was gleyic.

³Bulygina O.N. Razuvaev V.N. Korshunova N.N. and Shvets N.V. (2015). Climate Characteristics in North-Western Siberian Weather Stations. [online] Meteo.ru. Available at: <http://meteo.ru/data> [Accessed 20 Oct. 2025].

⁴System of Automatized Geocryological Monitoring of the Yamal-Nenets Autonomous Okrug. [online]. Monitoring.arctic.yanao.ru. Available at: <https://monitoring.arctic.yanao.ru/> (Accessed 20 Oct. 2025).

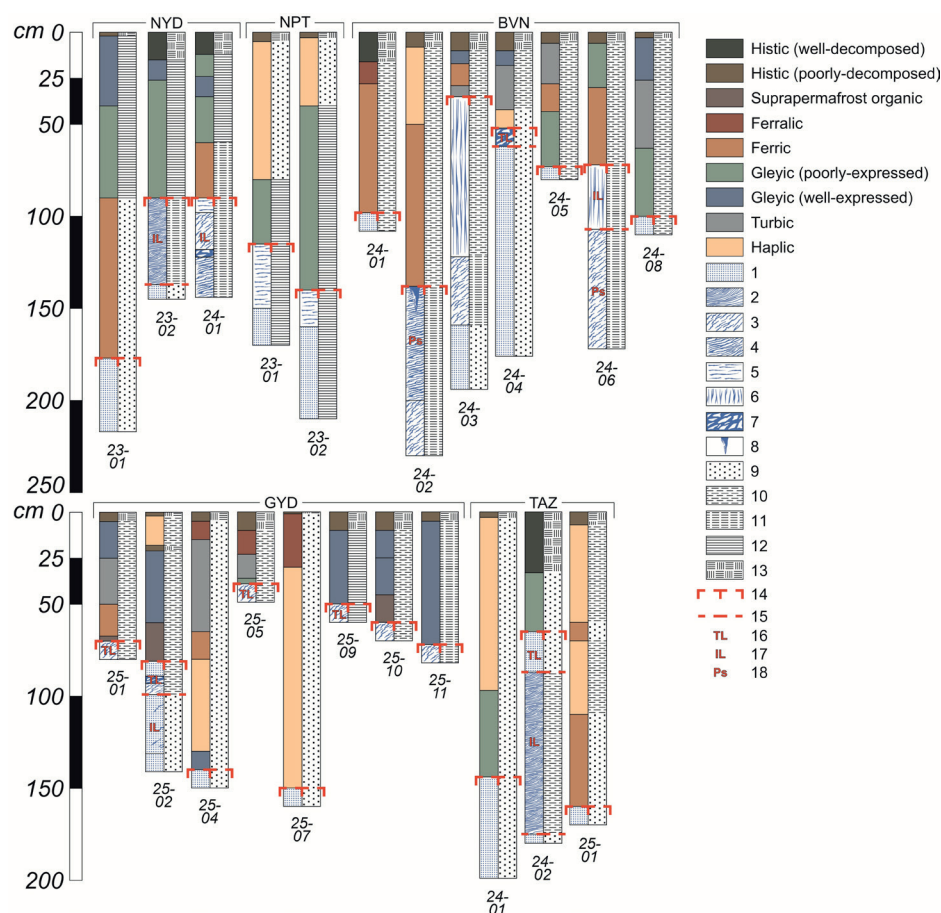


Fig. 2. Structure of the studied SCC. Soil horizons are given according to (IUSS... 2022). Cryostructures (by (Kanevskiy et al. 2014)): 1 – massive; 2 – reticulate; 3 – braided; 4 – thin-braided; 5 – lenticular; 6 – vein; 7 – ataxitic; 8 – ice wedges. **Soil texture classes:** 9 – sand; 10 – sandy loam; 11 – sandy loam to loam; 12 – loam (incl. silty loam); 13 – peat. 14 – actual AL depth; 15 – estimated borders of TL and IL; 16 – transient layer; 17 – intermediate layer; 18 – Late Pleistocene permafrost. Detailed information in Table 2.

BVN key site

At the BVN key site, the variety of soil types included Turbic Gelic Podzols, Turbic Gelic Gleysols, and Cryosols. The number of soil formation processes in each soil type was specific; thus, the morphological structure of their profiles significantly varied. ALT varied from 54 to 140 cm depending on soil texture, organic horizon thickness, terrain, etc. (Fig. 2 – sections BVN). In some cases, ice-rich TL and IL were completely thawed, especially as a result of lateral thawing. In SCC with lower ALT, such signs of cryoturbation processes as vortex horizon structure and the presence of buried organic horizon fragments and plant residues were clearly expressed visually. These processes were most intense in SCC on flat hilltops. In some soil profiles there were subsurface gleyic mineral horizons.

TL and IL, visually expressed in some SCC sections, were moderate and ice-rich and characterized by vein, braided, and ataxitic cryogenic structure (>50% by visible volume), the occurrence of which depended on the sediment lithological properties. Some TL and IL contained plant residues of moderate and high decomposition degrees, thin 2–3 mm layers of which alternated with mineral layers, and ice-rich zones were associated with these organic layers. The mineral matrix of permafrost in TL and IL was predominantly gleyic.

GYD key site

At the GYD key site, the studied soils mostly were classified as Gleyic Cryosols, Gelic Gleysols, and Podzols, profiles of which were often partly or totally gleyic, especially

in the subsurface layers (Fig. 2 – sections GYD-25-01–04/09–11). Gleyization was observed in soils on elevated sandy and loamy terraces that were characterized by the coldest hydrothermal conditions within this key site, and ALT was lower there, ranging from 44 to 71 cm. The expression of cryogenic disturbances of the soil profiles was commonly low; however in some Cryosol profiles the cryoturbation features – “drops” and “tongues” – were clearly expressed. In contrast, Gleysol profiles demonstrated undisturbed horizontal profile structures and equal gley distribution. In the warmest terrain positions on slopes, the ALT reached depths of 140–150 cm. Upper parts of these profiles, and in some cases all the profiles, were disturbed by solifluction processes that were further intensified by cryoturbation.

Upper permafrost horizons on the GYD key site were moderate and ice-rich. Cryogenic textures in them were predominantly ataxitic and braided, and maximal ice content was observed in the uppermost permafrost layer, right under the ALT bottom. Lowermost permafrost horizons were ice-poor and of the massive cryogenic structure. TL and IL had a predominantly gleyic mineral matrix with rare sulfide patches. Other pedogenic signs that enrich the system of TL and IL were Fe oxides and different-sized fine-grained organic matter patches. All these signs accumulated there as a result of cryoturbation and vertical migration processes.

DISCUSSION

According to Shur (1988), the system of TL and IL develops in frozen loose sediments despite the differences in genesis and texture. Thus, these natural-historical bodies are

Table 2. Environmental conditions around the studied SCC sections in Northwestern Siberia

SCC	Landform	Soil type	Soil texture	Cryogenic microrelief	Vegetation cover		ALT, cm
					Type	Density, moisture	
BVN key site							
BVN-24-01	Marine terrace slope	Spodic Cambic Cryosol (Arenic)	Sandy loam to loam, incl. underlain by sand	Mounds	Grass dwarf-shrub moss	H, D	98
BVN-24-02	RTS outcrop	Protic Arenosol (Arenic, Abruptic, Turbic)				M, D	138
BVN-24-03	Marine terrace summit	Turbic Cryosol (Arenic, Limnic)			Grass dwarf-shrub moss lichen	H, D	54
BVN-24-04	Marine terrace slope			Shrub grass moss lichen		52	
BVN-24-05	Marine terrace summit	Spodic Cambic Cryosol (Arenic)		-	Grass dwarf-shrub moss		75
BVN-24-06	RTS outcrop	Turbic Cryosol (Loamic, Abruptic)		Mounds			80
BVN-24-08	Marine terrace slope	Reductigleyic Gleysol (Loamic, Turbic)		Patches (frost boils)	Grass dwarf-shrub moss lichen	L, D	105
TAZ key site							
TAZ-24-01	Alluvial terrace summit	Protic Arenosol (Ferralic)	Sand to sandy loam	Patches (frost boils)	Moss lichen	L, D	145
TAZ-24-02	Lacustrine lowland	Turbic Histic Cryosol (Arenic, Limnic, Thixotropic)		-	Dwarf-shrub moss lichen	H, M	66
TAZ-25-01	Alluvial terrace slope	Protic Arenosol (Ferralic, Turbic)		Patches (frost boils)	Moss lichen	L, D	160
GYD key site							
GYD-25-01	Marine terrace slope	Turbic Cambic Cryosol (Arenic)	Sandy loam	Mounds, frost cracks	Grass dwarf-shrub moss lichen	H, M	71
GYD-25-02	Marine terrace summit			-	Grass (disturbed)	H, D	81
GYD-25-04	Lacustrine lowland outcrop	Albic Podzol (Arenic, Turbic)		Frost cracks	Grass dwarf-shrub moss	M, D	140
GYD-25-05	Lacustrine lowland	Spodic Cambic Cryosol (Arenic)		Mounds	Dwarf-shrub moss lichen	H, M	48
GYD-25-07	Alluvial terrace slope	Yermic Arenosol (Fluvic)		Solifluction terraces	Shrub horsetail	M, D	150

GYD-25-09	Alluvial terrace summit	Turbic Oxyaquic Cryosol (Loamic, Thixotropic)	Silty loam	Mounds	Grass dwarf-shrub moss lichen	H, M	50
GYD-25-10	Alluvial terrace summit	Turbic Cryosol (Arenic, Fluvic)	Sandy loam	-		H, D	59
GYD-25-11	Marine terrace slope	Turbic Reductaquic Cryosol (Loamic, Sulfidic, Thixotropic)	Loam	-	Shrub grass moss	H, W	72
NYD key site							
NYD-23-01	Lacustrine terrace shoulder	Reductigleyic Gleysol (Loamic, Limnic)	Loam to silty loam underlain by sand	Solifluction terraces, patches (frost boils)	Moss lichen	L, M	180
NYD-23-02	Lacustrine terrace slope	Turbic Cryosol (Loamic, Limnic, Thixotropic)		Solifluction terraces	Grass dwarf-shrub moss lichen	H, D	90
NYD-24-01	Lacustrine terrace summit	Reductaquic Cryosol (Loamic, Limnic, Thixotropic)		-		H, W	90
NPT key site							
NPT-23-01	Alluvial terrace summit	Aeolic Protic Arenosol (Fluvic)	Sand to sandy loam underlain by silty clay	Patches (frost boils)	Moss lichen	L, D	120
NPT-23-02	Alluvial terrace shoulder						140

Notes: "-" stands for the absence of cryogenic microrelief. Vegetation cover density classes: L – low, M – middle, H – high. Moisture classes: D – dry, M – moist, W – wet. RTS – retrogressive thaw slump.

widely distributed in the Northern Hemisphere permafrost zone, especially in lowland coastal plains with tundra environments (Gubin, Veremeeva 2010; Mergelov, Targulian 2011; Kanevskiy et al. 2014; Lacelle et al. 2019; Lupachev, Gubin 2023). However, in several regions where environment development processes were more comprehensive (e.g., sources of the soil-forming materials changed each other or sharp environmental shifts occurred), it was shown that these diagnostic criteria do not easily allow distinguishing permafrost parts of SCC. In polar environments of the Western Russian Arctic (e.g., Bolshezemelskaya Tundra, North-Eastern European Russia) TL and IL could not be strongly identified using visual features only (Kaverin et al. 2012). During this study, we have also faced methodological problems with TL and IL distinguishing in the SCC research at the Yamal and Gydan peninsulas.

In this regard, we summarized ALT monitoring data that were accumulated over the periods of 3–32 years at 5 CALM polygons or long-term ALT measuring transects⁵. Despite their predominant location on automorphic landforms – terrace summits or slopes, including those covered with polygonal peatlands (Fig. 3) – presented data mostly demonstrate ALT dynamics in these regions. Accounting for the different exact ALT measuring days at each site, we used only a 50% interval (between quartiles 25 and 75%) to estimate the approximate TL thickness.

The main factor that determines ALT as well as vegetation cover density is the soil texture. The largest variation intervals and deepest thawing among all observed sites are typical for sandy soils and ALT decreases in a row: sands – sandy loam – loam – peat (Fig. 3). Polygonal peatlands demonstrate not only the lowest mean ALT but also the narrowest variations across observation periods. It determines the approximate TL thickness of 1.9–6.0 cm. Polygonal peatland showing no signs of ice wedge degradation exhibits an interquartile (Q25–Q75) interval approximately twice as wide (Fig. 3). At the BVN key site, approximate TL thicknesses varied from 6.5 to 16.2 cm, with the lowest values associated with sandy loam to loamy soils. Relatively low TL thickness under the sandy soils at the TAZ key site could be explained by the stable seasonal thawing conditions there for the relatively short observation period (Fig. 3). The attached data on ALT measurements at key sites in Northwestern Siberia demonstrate the great inter-landscape variability of mean ALT, multiannual ALT variation intervals, and approximate TL thicknesses. Thus, the relatively thin layer (likely no more than 15 cm) in the upper part of frozen sediments could be considered as the TL here. In some of the studied SCC sections the ice-rich ataxitic layers (approximately 10 cm-thick) were described in the uppermost part of permafrost (Fig. 3).

⁵<https://www2.gwu.edu/~calm/data/north.htm>

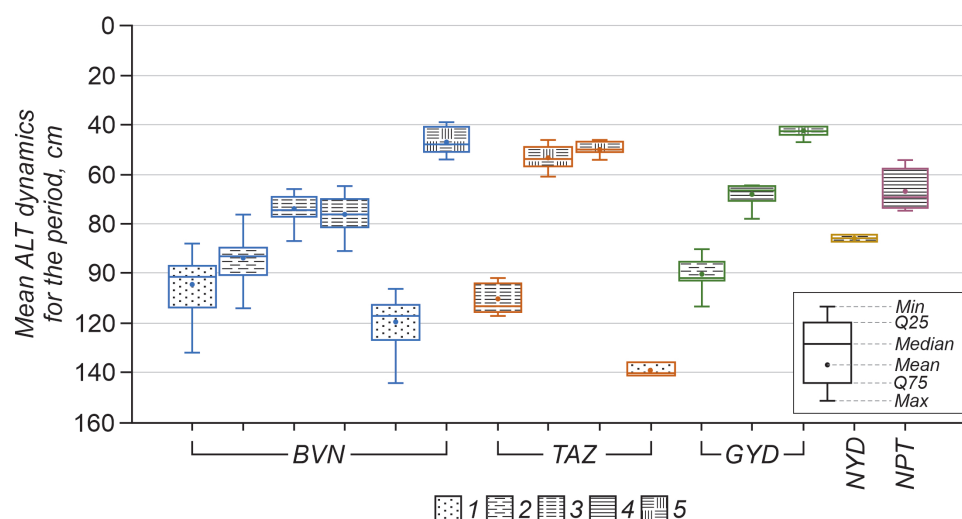


Fig. 3. Mean ALT dynamics for the observation periods based on CALM sites⁶ and ALT-monitoring transect data [Khomutov et al., 2024]. Soil texture classes: 1 – sand, 2 – sandy loam, 3 – sandy loam to loam, 4 – loam, 5 – peat. See all detailed information in the supplementary materials

Since the majority of the studied SCC developed in automorphic conditions, most likely the development of TL was driven by exclusively climatic factors, i.e., interannual ALT variation. The presence of the IL was most often observed in the SCCs at the uppermost surfaces of terraces (Table 2).

Processes of mineral material sedimentation in Northwestern Siberia were associated predominantly with marine and fluvial accumulation. That is why light-textured sediments occupy a major part of the region. This has resulted in the specificity of sediment cryogenic structures. In the outcrop of sandy-loamy marine terrace at Belyi Island, Slagoda and co-authors (2013) identified a TL with latticed cryostructure at the depth of 30–40 cm. That could be explained by relatively shallow average ALT at Belyi Island, even in sand (Khitun et al. 2011). Central and southern parts of Northwestern Siberian tundra, covered with sandy sediments, are characterized by relatively high ALT in comparison with other more heavily textured soil-forming materials (Khomutov et al. 2024). For that reason, the cryogenic structure of frozen sands could not be confidently used as diagnostic criteria for TL and IL subdivision without considering any other features. More than 70% of the studied SCCs were from fine sand to sandy loam, and cryogenic structures of their TL were massive, layered, and (far less commonly) braided (Fig. 2). The absence of ataxitic cryogenic structures in the studied SCC could be explained by the gradual AL deepening due to the fact that the ice-rich TL probably has already thawed.

Abakumov et al. (2017), based on geoelectrical research at the northern Gydan Peninsula and Belyi Island, showed that the deeper the thawing, the smoother the rise of the specific electrical resistance at the boundary between the AL and the underlying permafrost. This change of the resistance was highest in the ice-rich TL and IL, especially under the thick uppermost peat horizon of the soils. Thus, the thicker the peat cover, the higher the probability of the full three-element composition of the SCC existing beneath it. Kanevskiy et al. (2005) showed that at Marre-Sale Cape the ice-rich TL of nearly 20 cm thickness was preserved only under the mossy-peaty cover of at least 30 cm depth. Oblogov et al. (2023) also demonstrated that this uppermost permafrost layer is the most ice-rich within the entire 10-m permafrost exposure at Marre-Sale Cape. They suggest that the relatively shallow ALT (~40 cm) remains stable solely due

to the thick peat cover, noting that ALT in wet polygonal tundra has remained stable over the past ~40 years, while neighboring drained tundra has experienced a marked ALT increase. Tikhonravova et al. (2019) and Opokina et al. (2024) demonstrated that thick peat cover preserves not only the ice-rich cryogenic texture but even the small rejuvenated Holocene ice wedges in the IL of permafrost, which can be interpreted as its strong diagnostic feature (Koroleva et al. 2021). We observed a similar structure of the soil-cryogenic complexes in the northern part of the Pur-Taz interfluvium, where peat cover was about 30 cm thick, the total ALT was around 65 cm, and the system of the TL and IL of permafrost comprised a nearly 1-meter-thick ice-rich mass with the braided and ataxitic cryogenic structure. Thus, the main factor that protects SCCs of Northwestern Siberia from degradation under the current climatic trends of rising air temperatures is the local environmental conditions of soils (the degree of hydromorphic expression and the moss-peat cover thickness).

Limited suprapermafrost and intrapermafrost SOM accumulation is rarely expressed in SCC cores and outcrops in the tundra zone of West Siberia, which also complicates its morphological identification. Cryoturbation is observed as one of the most important processes of the TL-IL system enrichment with SOM (including coarse and fine SOM fragments) (Kaiser et al. 2007; Gentsch et al. 2015; Lupachev, Gubin 2023). In the northeastern part of Siberia strongly cryoturbated soils occupy the majority of automorphic surfaces in the coastal lowland areas (Gubin, Lupachev 2020). A combination of cryoturbation and shallow ALT in loamy sediments leads to great variability of organic-rich patches and layers in cryogenic soils and upper permafrost (Gubin, Lupachev 2018). However, according to Gerasimova (2007), cryoturbated soils (Turbic Cryosols) occupy a far smaller percentage of the total area in Northwestern Siberia in comparison with Middle and North-East Siberia. Another reason why suprapermafrost and upper permafrost layers of the West-Siberian SCC are depleted by SOM refers to the light (e.g., sandy) texture of soils. Sandy permafrost-affected soils (Sandy Podzols, Arenosols etc.) in Northwestern Siberia are rarely affected by intensive cryoturbation in their middle and lowermost parts (Walker et al. 2009).

For that reason, the pressing challenge is to identify alternative indicators that could be used to distinguish

⁶CALM North Summary Data Table [online] (2026). www2.gwu.edu/~calm/data/north.htm (Accessed 10 Feb. 2026).

the TL and IL. Based on the consideration that pedogenic processes take an important part in the formation of TL and IL structure and composition (Lupachev, Gubin 2008; 2023), we can suggest that several biogeochemical properties could be interpreted as the result of organic and mineral matter interactions between the soil profile and upper permafrost horizons. The C:N ratio is widely used in soil science and biogeochemistry as the degree of SOM decomposition. Lacelle et al. (2019) showed that in the Canadian Arctic coastal lowlands, the C:N ratio in the AL exceeds that in the TL by more than 25% in some cases. The reason is, probably, that modern AL (including its suprapermafrost part) is enriched with raw organic matter of relatively low decomposition degree, transferred into it through cryoturbation processes. The same authors demonstrate that TL is almost indistinguishable from the underlying permafrost by C and N total concentrations and C:N ratio values. At the same time, total S concentration marks the TL-IL transition quite well. In the TL it is characterized by the widest range and higher values in comparison with the AL and lower permafrost layers as well. Perhaps the reason is that the permafrost formed under predominantly reductive conditions, where S crystallized in the form of sulfide minerals (Lacelle et al. 2019). Similar features were observed in permafrost cores from the SCCs of the GYD and BVN key sites, where the gleyic mineral matrices contained abundant small sulfide spots. Lupachev and Gubin (2023) interpreted them as the sign of the reductive hydromorphic SCC development stage of the soil formation processes on the Kolyma lowland in the Mid-Holocene.

It has also been noted that among all biogenic compounds enriching the permafrost TL, methane plays an important role (Oblogov et al. 2020; Kim et al. 2025). The biogenic CH_4 content in the TL of permafrost in the Marre-Sale Cape, western Yamal, is slightly higher compared to the overlying AL and underlying permafrost. The mechanism of the TL enrichment with biogenic gases (CH_4 and CO_2) can be commonly explained by the blocking role of downward freezing at the start of winter that presses the gases from the AL and preserves them in the upper permafrost layers (Kraev et al. 2017; Oblogov et al. 2020; Kim et al. 2025). Besides, another way of upper ice-rich permafrost enrichment with gases is possible in a number of permafrost regions – upward filtration and accumulation below the TL-IL system bottom. This way could be especially typical for the West Siberian permafrost zone, where deposits contain large amounts of hydrocarbon gases and gas hydrates (Khimenkov et al. 2020). Via gas-hydrate dissociation gases filter through the permafrost, and TL-IL systems can become natural barriers on the migration way because of their high ice volume. The results of the laboratory experiments held by Chuvilin and co-authors were that ice-rich frozen sediments are approximately impenetrable for fluids under the low negative temperatures. As temperatures rise, the gas permeability increases significantly even before thawing (Chuvilin et al. 2024).

As a result of downward vertical migration, the reactive chemical compounds (K_2O , P_2O_5 , Fe_2O_3 , MnO , etc.) can accumulate in the suprapermafrost parts of soil profiles and be preserved in the upper permafrost layers (Jones et al. 2020). Some of them could be considered exclusively pedogenic, formed via biochemical processes in soils, e.g., non-silicate Fe compounds (Zonn 1982).

The most commonly used approach to diagnose the TL and IL is the cryolithological differentiation of layers based on their cryostructure (Shur 1988). TL is often

considered the most ice-rich layer in the upper section of permafrost underlying AL. The IL is also characterized by relatively high ice content compared with underlying Late Pleistocene deposits. This feature is typical of regions such as the Northeastern Yakutia coastal plains, where SCCs were mainly described (Lupachev, Gubin 2023). In other regions where the upper permafrost contains ice-rich sequences (like Northwestern Siberia) (Streletskaia et al. 2021), distinguishing TL and especially IL meets certain difficulties.

In some studies, it was stated that TL of permafrost contains large amounts of SOM, both its fine and coarse fractions (Kaiser et al. 2007; Mergelov, Targulian 2011; Gentsch et al. 2015; Lupachev, Gubin 2023; Cherepanova, Shepelev 2023) via processes of cryogenic mass exchange within the AL. Alekseev and co-authors (2003) discovered the possibility for the colored Fe mineral lepidocrocite to accumulate at the bottom of the AL, which also could be considered as a diagnostic criterion for AL depth. Maslakov and colleagues (2020) applied the isotopic analysis of textural ice showing that $\delta^{18}\text{O}$ values in the TL vary within the narrow interval between -14 and -11‰ , indicating periodic TL thawing and enrichment with atmospheric waters with “heavier” isotopes. Observing the TL and IL system in frozen polygonal peatlands with ice wedges, Koroleva and co-authors (2021) noted that in some cases the so-called “wedge sprouts” can penetrate the IL indicating the modern stage of frost cracking process.

At present, a major part of Northwestern Siberia is characterized by a pronounced trend of permafrost zone area and vertical thickness reduction against the backdrop of warming and humidifying climatic shifts (Vasiliev et al. 2024). Consequently, the number of geomorphological cryogenic processes is conditioned by the upper ice-rich permafrost layer dynamics via thaw ground subsidence (Streletskiy et al. 2025), thermal denudation (Nesterova et al. 2025), thermal abrasion in the coastal areas (Isaev et al. 2018). Until 2050, the significant expansion of the area exposed to various destructive cryogenic processes is projected (Kislov et al. 2023). SCCs of Western Siberian tundra are extremely unstable to modern climate change. The areas with full-profile SCCs, where the TL-IL system plays the shielding role and protects underlying permafrost and massive ground ice, are relatively limited in spatial distribution. The SCC sections with partially or totally thawed TL occur the most often, and the ALT there reaches the IL. The NYD-24-01 SCC section was presumably of such type: its frozen part differed markedly from the thawed soil profile – it consisted of an ochric-gray-colored mineral matrix where the modern AL was dominantly gleyic. The TL forms under the influence of cryogenic mass-exchange processes, and the lowermost part of the AL can not differ markedly from it; thus, the TL presumably degraded completely here. Soils on light-textured sediments of the southern part of the Yamal and Gydan peninsulas and northern Pur-Taz interfluvium are often characterized by the full absence of the TL and IL in the system of SCC. Probably, the sharp transition from the active layer to the underlying permafrost shows the physico-chemical features of the shift of the environmental conditions here in the Early Holocene. BVN-24-02 section had an AL of nearly 140 cm depth due to the lateral heating of the thaw slump wall. The isotopic composition of the ground ice wedge head in the uppermost permafrost layer was similar to the earlier studied Late Pleistocene ones in the region (Vasil'chuk 2025 – personal communication), thus we conclude that the TL and IL fully degraded because rejuvenated ice wedges in the IL can possibly be of Holocene age only.

CONCLUSIONS

During the first stage of detailed SCC research in Northwestern Siberian tundra environments, we obtained initial results on the morphological and cryogenic structure of thawed and frozen parts of the SCC and attempted to broaden the approaches to TL and IL diagnostics in the upper part of permafrost in different landscapes.

Regardless of the geomorphological level, SCCs of the permafrost zone of Western Siberia share a common characteristic: their full-profile variants, comprising two main structural elements – TL and IL – are spatially limited due to lithogenic and ecosystem factors. The widest distribution of deeply thawing sandy sediments where continuous and thick vegetation cover is unable to develop due to its depletion in nutrients and active wind erosion that destroys the root layer prevents the full-profile SCC development in modern conditions. Among all studied SCCs, the ALT was the highest in sandy soils, and morphologically expressed TL was absent. Modern soil formation took place in the seasonally thawed layer that overlies the degrading IL or Late Pleistocene permafrost, containing fragments of ground ice (massive or wedge). Besides, relatively low ice content in sands rarely allows one to confidently differentiate TL and IL by visual cryolithological signs (ice volume and inclusions), and such features as organic concentration zones (with raw poorly-decomposed plant residues) typical for some permafrost regions (Kolyma, European North-East Russia, Alaska), were observed here

only in individual SCC sections where average ALT was below 40–60 cm. The intra-annual temperature gradients in such soils were highest, and that is why cryogenic mass exchange properties were most intensive. It was also a methodological challenge to distinguish the TL and IL in the complex polygenetic structure of some SCC frozen parts. In some of them periods of deepened thaw were accompanied by sediment redistribution, burying organic layers and exposing mineral material. Transition from synlithogenic soil formation to postlithogenic introduces several characteristics that complicate the morphological identification of TL and IL in the SCC.

For a major part of the studied key sites, the Holocene was probably a period of variable-intensity soil-permafrost cryogenic mass exchange. These fluctuations were explained by the wide intervals of soil thawing, especially on sandy sediments. Relatively stable permafrost conditions were in the thick peat massifs only. The presence of thick organic horizons on the soil surface that reduces the heat fluxes into soils and limits the ALT is the leading factor of the thawing stabilization. Only in such cases, the full-profile SCCs still remain even in mineral sediments.

Developing the diagnostic criteria to raise the confidence of TL and IL diagnostics (or assessment of their partial or complete thawing) in permafrost layers is under future consideration. Biogeochemical parameters, micromorphological indicators of pedogenesis, and the chemical composition of textural ice are among the candidates for such diagnostic criteria. ■

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THE HISTORY OF DISTRIBUTION OF THE FAMILY LECYTHIDACEAE S. L.

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ABSTRACT. The modern distribution and dispersal history of the family Lecythidaceae s. l. present scientific interest so far as Lecythidaceae has a pantropical areal, thus forming several disjunctions, that may represent ancient continental contacts. Species of this family are distributed in Central America, firstly in the subequatorial and equatorial areas of South America, particularly, in Amazon Basin and some zones of Northern and Central Andes, in the equatorial forests of Congo Basin, along the Gulf of Guinea in Africa, and in South and Southeast Asia. Species of the family are also found in Australia and also in some Oceania Islands. According to modern data, the family, which is part of the order Ericales, includes 30 genera and 395 species [PoWO 2025]. The purpose of research is to point a hypothetical center of origin of the entire family and reconstruct the spreading routes of family species and genera. Several morphological and ecological features (mostly pollination and dissemination) of family representatives were analyzed and compiled. The molecular genetic data for selected taxa of Lecythidaceae s. l. was also analyzed and the results of reconstructing probable dispersal routes were compared with available paleobotanical materials. The resulting molecular genetic model was calibrated according to age of found fossils. The parsimony reconstruction of hypothetical dispersal tracks and dispersal ways of Lecythidaceae s. l. species and genera was based on a detailed calibrated model and became the result of this research. A hypothetical center of origin for the ancestor of the family Lecythidaceae s. l. was identified.

KEYWORDS: Phytogeography, Dispersal tracks, Molecular-genetic analyses, Calibration based on available paleobotanical data

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INTRODUCTION

The family Lecythidaceae s. l., which is part of the order Ericales, includes 30 genera and 395 species. It has a pantropical range. Genera such as *Lecythis*, *Allantoma*, *Gustavia*, *Corythophora*, *Couratari*, *Couroupita*, *Grias*, *Cariniana*, *Bertholletia*, *Asteranthos* and *Eschweilera* are native to South America and are mostly found in Amazon basin, the territory of modern day Colombia, Venezuela, Guyana, Suriname and French Guiana, as well as eastern and central Brazil. Many species of these genera also grow in Central America. Species of the genera *Napoleonaea*, *Foetidia*, *Rhaptopetalum*, *Brazzeia*, *Scyttopetalum*, and *Petersianthus* inhabit large areas of Central Africa, particularly the Congo River basin. Finally, the areal of species of *Barringtonia*, *Careya*, *Planchonia* and

Chydenanthus covers Southeast Asia, Northern Australia, several islands in Oceania. Also, some species of the genus *Barringtonia* grow in Madagascar.

Species of the family Lecythidaceae s. l. are large and very large trees, up to 55 meters tall, such as *Bertholletia* [Prance & Mori 2004], or, more rare, small trees, or less commonly, shrubs. The leaves are always alternate and simple. The flowers of some species of the family Lecythidaceae s. l. form inflorescences, but many species have solitary flowers. The inflorescences are represented by simple racemes or panicles. Other types of inflorescences specific for the family can be named derivatives of panicles [Appel 1996]. The flowers are bisexual, can be actinomorphic or zygomorphic and have a peduncle or sessile bracts in the axil. Some species of the family, such as the genus *Napoleonaea*, present the formation of flowers directly on

the stem – cauliflory [Prance 2004]. Sepals are usually 2 to 6 and they are often free, but sometimes (particularly in members of the subfamily Scytopetaloidae) they are fused into a single calyx, often thick and leathery. Petals are usually 3 to 6, but in several species, they are 8. The members' of the subfamily Napoleonaeoidae petals are fused into a ribbed corolla consisting of 30–35 segments, or true petals are absent, and the outer circle of sterilized stamens forms a pseudocorolla. The subfamily Scytopetaloidae species have no petals, but have an outer circle of sterile stamens that form a pseudocorolla. Lecythidaceae species have many stamens, from 10 to 1210 (possibly more), often fused at the bases of the filaments. The flowers form several whorls of stamens, sometimes fused at the base, and several whorls of morphologically similar staminodes. Often this partially fused androecium forms a cap, which has varying configurations. The gynoecium is coenocarpous; the ovary is usually inferior, although it can also be semiinferior (*Asteranthos*, *Crateranthos*) or superior (in species of Scytopetaloidae, except *Asteranthos*). It consists of 2, 3, 4, or 6, rarely 8, locules, each containing from 2 to a huge number of ovules. The fruits are indehiscent dry, leathery or even woody pyrenaria, or capsules, which often have a unique rounded "lid" [Prance & Mori 1978]. The embryo of Lecythidaceae s. l. species is usually large, straight or curved. Actinomorphic flowers of the family species are pollinated mostly by bees, but field observations of these plants have shown that some beetles and even bats also actively visit the flowers; however, this fact requires more detailed study [Prance & Mori 2004]. Species of the genus *Gustavia*, according on the available data, provide parts of the pollen as a "reward" for visiting bees, which further encourages them to visit the flowers [Mori & Boeke 1987]. The flowers of many species of the genus *Grias* secrete unique acids that have a special fragrance, which attracts pollinating beetles [Knudsen & Mori 1996]. Pollination processes of Lecythidaceae s. l. species, which have zygomorphic flowers, are more difficult. The specific ways depend mostly on the complexity and openness of the androecium, as well as on the benefit each flower of a particular species provides to the pollinating animal [Mori 1989]. For example, some species (*Lecythis zabuajo*) produce specific pollen grains in the open anther cap, and the others (*Corythophora rimosa*) produce such pollen in the closed cap. Some of species (*Lecythis corrugata*) produce a combination of pollen grains and nectar grains, which are located in the closed cap of the androecium. Finally, the most highly organized species (in particular, the genera *Eschweilera* and *Couratari*) offer pollinators nectar directly from the closed stamen cap [Prance & Mori 2004]. Visitors of these flowers are also mostly bees. However, there are at least two species with zygomorphic flowers (*Lecythis poiteaui*, *Lecythis barnebyi*) were visited by bats; however, this point requires further research and confirmation [Mori, Prance & Bolten 1978; Mori, Prance & Zeeuw 1990]. A detailed study of pollination processes didn't reveal any individual relationships between specific Lecythidaceae species and specific bee species, which are the most active pollinators. The only connection that exists in these relationships is that the pollinator must be large enough to open the anther cap (of course, only if it is closed) and have a long proboscis to reach the pollen and nectar located inside the cap [Prance & Mori 2004]. For example, species of such genera of bees and bumblebees as *Bombus*, *Centris*, *Epicharis*, *Eulaema* and *Xylocopa* often fly into the flowers of the genus *Bertholletia* [Mori & Prance 1990; Mori 1992]. The flowers of *Eschweilera pedicellata* are visited exclusively by bees of the tribe Euglossini, which are

the only New World bees whose proboscis is long enough to extract pollen from the closed stamen cap. Due to the great variety of fruits, dissemination of different species of the family Lecythidaceae s. l. also differs in many forms and ways. Some species of the genus *Barringtonia* (in particular *B. racemosa* and *B. acutangula*) have large, but not dense, floating fruits, which, according to available data, are spreading by ocean currents, which explains the wide area of the genus. Many fruits of other genera are dispersed similarly, which suggests that one of the mostly used methods of dissemination of these plants is hydrochory. Fruits of many other genera, for example, *Couroupita*, *Grias* and *Gustavia*, have combined methods of dissemination. In particular, it was noted that after dehiscence of hard and heavy fruits, seeds that contained in the fruit are dispersed by many species of forest mammals (agouti or many species of monkeys), and seeds that fall into water are dispersed by fish [Prance & Mori 1978; 1979]. Other Lecythidaceae genera, such as *Cariniana* and *Couratari*, have dehiscent fruits with winged seeds inside, which represents anemochory. Also, the seeds of some species of the genus *Lecythis*, whose fruits also dehisce, are dispersed by bats [Prance & Mori 2004].

There is very little paleobotanical data that would allow us to talk about the origin of the entire family or its individual taxa. There are known finds of *Lecythidoanthus kugleri* [Berry 1924a; 1924b], whose flower has features of the species of subfamily Lecythidoideae. The age of this find is dated to the Miocene. Wood of the plant *Lecythioxylon brasiliense* [Milanez 1935], dated to the Cretaceous, was also described. In 1960, the possible ancestor of species of the subfamily Barringtonioideae, *Barringtonioxylon deccanense* [Shallom 1960], was described, as well as the closely related *Barringtonioxylon eopterocarpum*, which are dated to the Upper Cretaceous [Prakash & Dayal 1965]. In 1969, a fossil fruit from Colombia was described and it present morphological similarities to fruits of the genus *Eschweilera*. This plant was named *Lecythidopyxion girardonatum* [Huertas 1969]. Pollen from several extinct plants has also been found in India and Borneo, possibly of the genera *Barringtonia* and *Chidenanthus*, dating to the Eocene. Finally, some pollen was found in Cameroon, which is similar to pollen from the genera *Barringtonia* and *Planchonia* and also dating to the Eocene [Tsou 1994].

MATERIALS AND METHODS

To research the dispersal history of the family Lecythidaceae s. l. and to construct possible tracks, species included in different genera, presenting variety of morphological and ecological similarities and differences, and growing in different parts of the family's areal were selected for analysis. Thus, 40 species were analyzed, including a species from the outgroup: 5 species each from the genera *Lecythis* and *Barringtonia*, 3 species each from the genera *Gustavia*, *Grias*, *Napoleonaea*, and *Foetidia*, 2 species each from the genera *Couratari* and *Couroupita*, and 1 representative each from the genera *Allantoma*, *Corythophora*, *Bertholletia*, *Asteranthos*, *Rhaptopetalum*, *Scytopetalum*, *Petersianthus*, *Brazzeia*, *Careya*, *Cariniana*, *Eschweilera*, *Planchonia*, and *Chydenanthus*. The genera *Chytroma*, *Crateranthus*, *Guaiania*, *Imbiriba*, *Oubanguia*, *Pachylecythis*, *Pierrina*, *Scottmorra* and *Waimiria* were not studied analyzed due to the absent available material.

In our research, were used the cladistic method [Henning 1950]. The studied species, their areas, and the genes used in the research are listed below (Tab. 1).

Table 1. Access codes and ranges of the analyzed species

Species	Genes				Range
	trnL-trnF	matK	ndhF	rbcl	
<i>Impatiens balsamina</i>	EF649982.1	MN317471.1		MK526011.1	
<i>Lecythis ampla</i>	DQ418012.1		JN607452.1		Central America
<i>Lecythis barnebyi</i>	JN221947.1		JN607453.1		Central Amazon basin
<i>Lecythis lurida</i>	JN221958.1		JN607460.1		Amazon basin, Brazil Highlands
<i>Lecythis minor</i>	DQ418022.1		DQ388216.1		Central America, Guiana
<i>Lecythis retusa</i>	JN221972.1				Central Amazon basin
<i>Allantoma lineata</i>	DQ417929.1		JX164031.1	AF077657.1	Central Amazon basin, Guiana
<i>Gustavia augusta</i>	DQ418002.1		DQ388207.1	MF786277.1	Amazon basin
<i>Gustavia monocalis</i>	DQ418008.1		DQ388206.1		Central America
<i>Gustavia superba</i>	DQ418010.1	GQ982005.1	DQ388199.1	GQ981755.1	Central America
<i>Corythophora labriculata</i>	DQ417943.1		DQ388190.1		Guiana Highland
<i>Couratari calycina</i>	DQ 417945.1		DQ388192.1	JQ626169.1	Guiana Highland
<i>Couratari guianensis</i>	DQ417946.1	JQ626563.1	DQ388193.1	JQ626273.1	Guiana Highland
<i>Grias cauliflora</i>	DQ417997.1		DQ388179.1	AF077652.1	Central America
<i>Grias peruviana</i>	DQ417999.1		DQ388178.1		North Andes
<i>Grias multinervia</i>	DQ417998.1		DQ388272.1		Central America, North Andes
<i>Couroupita guianensis</i>	DQ417951.1		DQ388182.1	AF022134.1	Amazon basin, Guiana Highland, Central America, North Andes
<i>Couroupita nicaraguensis</i>	DQ417952.1		DQ388183.1		Central America, North Andes
<i>Cariniana rubra</i>			JX164036.1		Amazon basin, Brazil Highlands
<i>Bertholletia excelsa</i>	DQ417933.1		DQ388181.1	Z80178.1	Amazon basin, Guiana Highland
<i>Asteranthos brasiliensis</i>	AF077648.1			AF022133.1	Central Amazon basin
<i>Eschweilera integrifolia</i>	DQ417965.1		DQ388234.1		Central America, North Andes
<i>Napoleonaea imperialis</i>	DQ418031.1		AJ236258.1		Coast of Gulf of Guinea and Congo basin
<i>Napoleonaea heudelotii</i>				MN366490.1	Coast of Gulf of Guinea and Congo basin
<i>Napoleonaea gabonensis</i>		MN370170.1		MN366489.1	Coast of Gulf of Guinea and Congo basin
<i>Foetidia obliqua</i>	DQ417995.1		DQ388176.1		East Africa, Madagascar or Mascarenes
<i>Foetidia asymetrica</i>				Z80183.1	Madagascar or Mascarenes
<i>Foetidia mauritiana</i>	DQ417996.1		DQ388177.1		Madagascar or Mascarenes
<i>Rhaptopetalum coriaceum</i>	DQ418037.1				Coast of Gulf of Guinea and Congo basin
<i>Scytopetalum klaineum</i>	DQ418038.1	KC627646.1	DQ388166.1	KC628275.1	Coast of Gulf of Guinea and Congo basin
<i>Petersianthus macrocarpus</i>			DQ388172.1		Coast of Gulf of Guinea and Congo basin
<i>Brazzeia soyauxii</i>		MN370172.1		MN366488.1	Coast of Gulf of Guinea and Congo basin
<i>Barringtonia acutangula</i>		JN183985.1		AB925810.1	South Asia, Southeast Asia, Malesia, North Australia

<i>Barringtonia asiatica</i>	DQ417930.1	DQ924095.1	DQ924203.1	EU980812.1	South Asia, Southeast Asia, Malaysia, North Australia, East Africa, Madagascar or Mascarenes
<i>Barringtonia edulis</i>	DQ417931.1		DQ388174.1		Melanesia
<i>Barringtonia lanceolata</i>				MG784924.1	Malaysia
<i>Barringtonia racemosa</i>	DQ417932.1	KJ510928.1	DQ388175.1	MK529927.1	South Asia, Southeast Asia, Malaysia, North Australia, East Africa, Madagascar or Mascarenes
<i>Careya arborea</i>	DQ924313.1	MG742305.1	DQ924204.1	AF077655.1	South Asia, Southeast Asia
<i>Chydenanthus excelsus</i>	DQ417940.1		DQ388173.1		Southeast Asia, Malaysia
<i>Planchonia careya</i>		KM894763.1		KY661347.1	North Australia, Malaysia

Information on the ranges was taken from literary sources [Takhtadzhyan 1978; MOBOT 2025]. To reach the stated purposes, in particular, to obtain an objective "cladistic picture", it is necessary to include a species that is not closely related to the studied taxa (i.e., not included in the studied group), but "in general" taxonomically close (usually more basal) in the list of studied taxa as an outgroup [Abramson 2013]. In this study, the species *Impatiens balsamina* L. from the family Balsaminaceae was used as an outgroup. In the process of constructing cladograms in this study, two methods were used, representing the relationships within the family Lecythidaceae s. l., one of which is based on the analysis of molecular genetic data, and the second is used to establish hypothetical divergence times for specific clades and to calibrate the cladogram (the calibrated cladogram method). The molecular genetic method is based on the comparison of genetic characteristics, that is, the nucleotide sequences of individual DNA fragments in different taxa. The resulting cladogram is calibrated using available paleobotanical data and replenished with a visual representation of the ranges of the species included in it. For a more complete description of the processes involved in such analysis, it is necessary to describe these methods in more detail.

The molecular genetic analysis of analyzing taxa requires extensive data collection. Nucleotide sequences of four chloroplast markers were used for phylogenetic analysis. In our research, information of 40 species, including outgroup, was retrieved from the GenBank open database. These data are encoded in four sequence genes (the plastid maturase K gene (matK), the plastid ribulose biphosphate carboxoxidase gene (rbcl), the plastid NADH dehydrogenase complex gene (ndhF), and the trnL-trnF spacer). These genes were not analyzed for every species, as information on some of them is missing in GenBank. Also, since each species was sequenced using different algorithms and for different purposes, the number of nitrogenous bases, as well as the start and end locations of the sequences, didn't match. So, before the analysis, multiple sequence alignment was done using the Clustal W algorithm [Larkin et al. 2007]. The steps of processing the nucleotide sequences were implemented in the MEGA 11 program. Gaps (empty regions without nitrogenous bases) were encoded with the "-" symbol, and regions with an unknown set of nitrogenous bases were encoded with the "?" symbol. The aligned and most informative regions of the nucleotide sequences were connected into single chains for each of the analyzed taxa, and then, in the MEGA 11 program, a cladogram of the studied species was constructed. It was used the Tajima-Nei model with the maximum parsimony method, which is based on establishing proximity by minimizing the number of transformations of each character (i.e., minimizing the number of nucleotide substitutions) [Lemey, Salemi & Vandamme 2009]. Branch reliability was assessed using the

bootstrap method with a score of 5000 [Felsenstein 1985]. The number located on each branch indicates the percentage probability of the degree of the species relatedness. A probability greater than 70 is considered sufficient [Hillis & Bull 1993; Wiley & Lieberman 2011].

The calibrated cladogram method allows to determine the approximate divergence time of individual clades. The first step is to convert aligned nucleotide bases using the Clustal W method to the NEXUS (.nexus) format. MEGA 11 program allows to export alignment sessions to this format. Then, it is necessary to use the available paleobotanical data. For this purpose, divergence points of specific clades were specified in BEAUti ver. 2 Standard. These points were assigned a time corresponding to the geological period when these clades diverged, and they were also assigned a name identical to the Latin name of the fossil species Lecythidaceae s. l. To accurately calculate the data of the specified divergences, the corresponding taxa were placed on different sides of the bifurcation in the command field. The Strict Clock model was used as a model of evolutionary time. It assumes a correlation between the speed of evolution and the lengths of branches [Ferreira & Suchard 2008]. The JC69 model [Jukes & Cantor 1969], which compares the speed of appearance and substitution of mutations, was used as a replacement model. For the probability distribution of time intervals, the Yule model was used [Yule 1924; Simon 1955; Rose & Smith 2002]. The program also allows to choose a separate function for the probability distribution. The lognormal function was selected as the most optimal. For further calibration, the BEAST ver. 2.6.6 program was used. It constructed a large number of probable phylogenetic trees based on the available nucleotide base sequences and paleobotanical data. The number of such trees can be determined manually. So, a number of 500,000 models with a step of 1000 were selected. Then, it was necessary to reduce all the cladograms obtained during the analysis into a single "average", consensus cladogram. This was done using the program TreeAnnotator ver. 2.6.6. In this application, the percentage of pruning of the extreme probability trees for the next reduction was selected (it was equal to 20%). As a result of these operations, a file containing a single consensus phylogenetic tree was obtained. Finally, visualization of the result and stylization of the cladogram were done in the program FigTree ver. 1.4.4. The result was a calibrated cladogram, which also included paleobotanical data with the probable divergence times of individual clades from each other. The distribution of the time of evolutionary divergence is shown by the length of the lines at the bifurcation points.

Construction of area and distribution maps for analyzed taxa. A cartographic method was used to visualize the dispersal processes of taxa within the family Lecythidaceae s. l. The maps were created using QGIS ver. 3.22.6.

RESULTS

Molecular genetic model

Analyzing the model obtained using molecular-genetics data, a number of conclusions about the relationships between various species of the family Lecythidaceae *s. l.* was drawn and, based on these, probable routes of their dispersal (Fig. 1) were construct.

The configuration of the tree constructed using molecular-genetics data allows to divide it into several clades. The basalmost position includes three species of the genus *Napoleonaea*. According to structure, *N. heudelotii* and *N. imperialis* are more closely related than *N. gabonensis*, which is located in the most basal position of all the species analyzed. The second clade includes three African species of Lecythidaceae *s. l.* – *Rhaptopetalum coriaceum*, *Scytropetalum klaineum*, and *Brazzeia soyauxii*, as well as one South American species, *Asteranthos brasiliensis*. The last two taxa, according to the model, are sister to each other, and then paraphyly is observed for the first two. The next clade includes all the species of the genus *Barringtonia*. It has a bifurcation, based on which it

can be concluded that the species *B. edulis* and *B. asiatica*, as well as *B. acutangula* and *B. lanceolata*, are pairwise sister ones. The position between these pairs is contained with *B. racemosa*, which belongs to the same clade with the first two species and is more closely related to them than to the last two. Another clade has a bifurcation that pairwise unites four species. The first part of this bifurcation contains *Chydenanthus excelsus* and *Petersianthus macrocarpus*, indicating the close relationship between these genera. The second part contains *Careya arborea* and *Planchonia careya*. So, these genera can also be considered sister ones. The next clade includes three species of the genus *Foetidia*. *F. asymerica* and *F. mauritiana* are located in a sister position, and *F. obliqua* is the most basal here. Next goes a clade that bifurcates into branches including two large Neotropical genera – *Gustavia* and *Grias*. The close relationship between these genera is also confirmed by some molecular-genetic studies [Mori et al. 2015]. *Gustavia monocalis* and *G. superba* are sister genera, while *G. augusta* is located in a basal position. On the other side of this clade there is the genus *Grias*. *G. cauliflora* and *G. multinervia* are the sister species, with *G. peruviana*, which is the most basal.

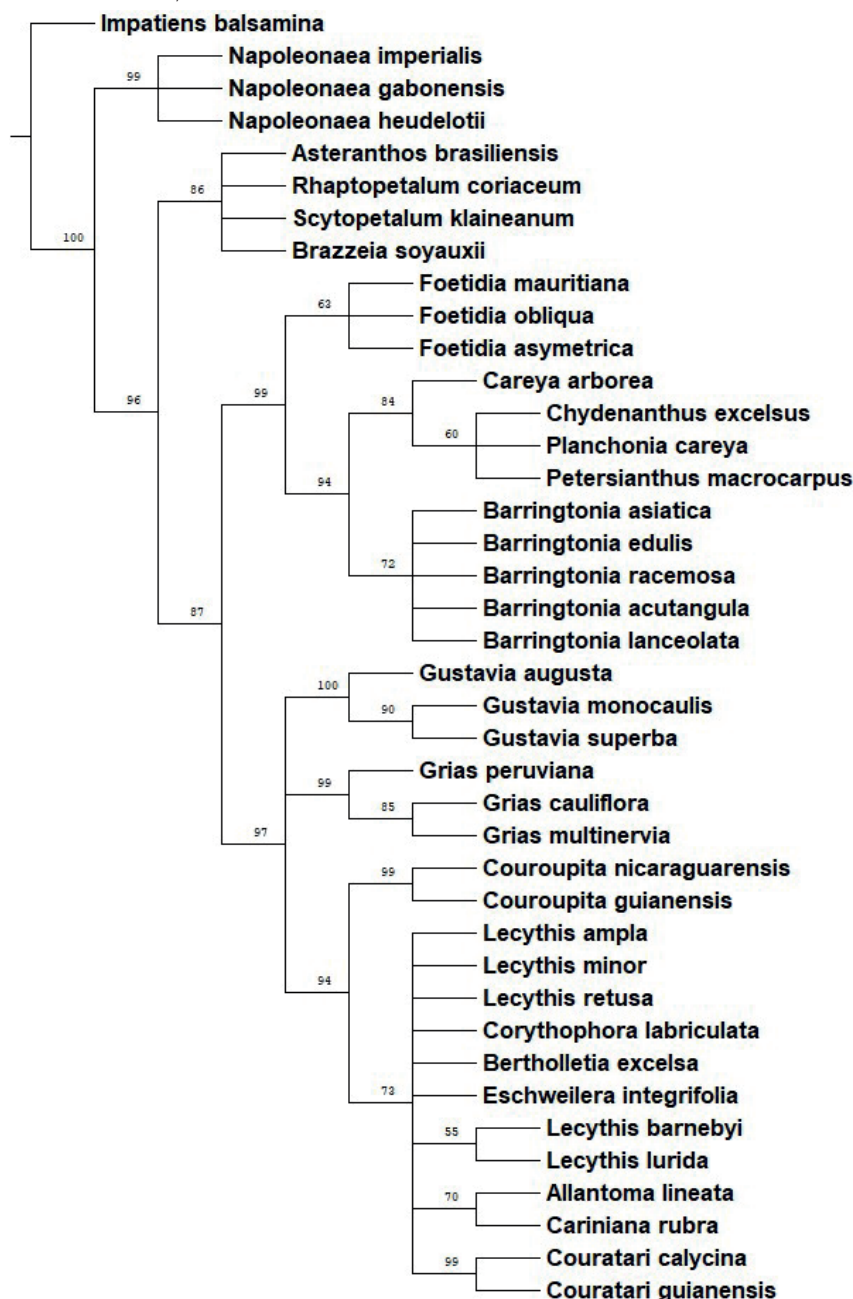


Fig. 1. Molecular genetic cladogram of *Lecythidaceae s. l.*

The indicated geological periods correspond to the subdivisions of the International Stratigraphic Chart and the boundaries ratified by the IUGS (International Union of Geological Sciences) as of March 2008 [Ogg, Ogg & Gradstein 2008]. Based on the calibrated model, it can be concluded that the family diverged approximately 85 million years ago, in the Late Cretaceous. It was also at this time that species of the Napoleonoideae (the basal

DISCUSSION

Their structure allows to reconstruct the possible taxa dispersal routes. Another important factor is the ecological conditions of modern species. Pollination and dissemination characteristics are key components of such reconstructions, as they often allow to determine the methods and ways of dispersal. Morphological similarities and differences make it possible to understand the degree of evolutionary relationship between individual taxa and to reconstruct some hypothetical processes that occurred with their vegetative and reproductive organs. However, in this research, the molecular-genetic cladogram is the foundation for reconstructing possible dispersal routes. Based on phylogenetic relationships, the basal group (closest to the "root" of the cladogram) was determined, the possible region of taxon formation, and the tracks of their dispersal were identified. The results of the molecular genetic model of the relationships between the taxa of *Lecythydaceae s. l.* confirm that the basal taxon is the genus *Napoleonaea*, which with the genus *Crateranthus*, grows in the Guinea-Congo floristic region. In particular, *Napoleonaea gabonensis* grows in the Congo River Delta region, *N. heudelotii* – in the western part of this region, on the coast of the Gulf of Guinea, and *N. imperialis* has a wide area, growing almost everywhere in Guinea-Congo region [Takhtadzhyan 1978]. This fact allow to consider the range of the subfamily Napoleonoideae the hypothetical region of origin of the whole family *Lecythydaceae s. l.* According to

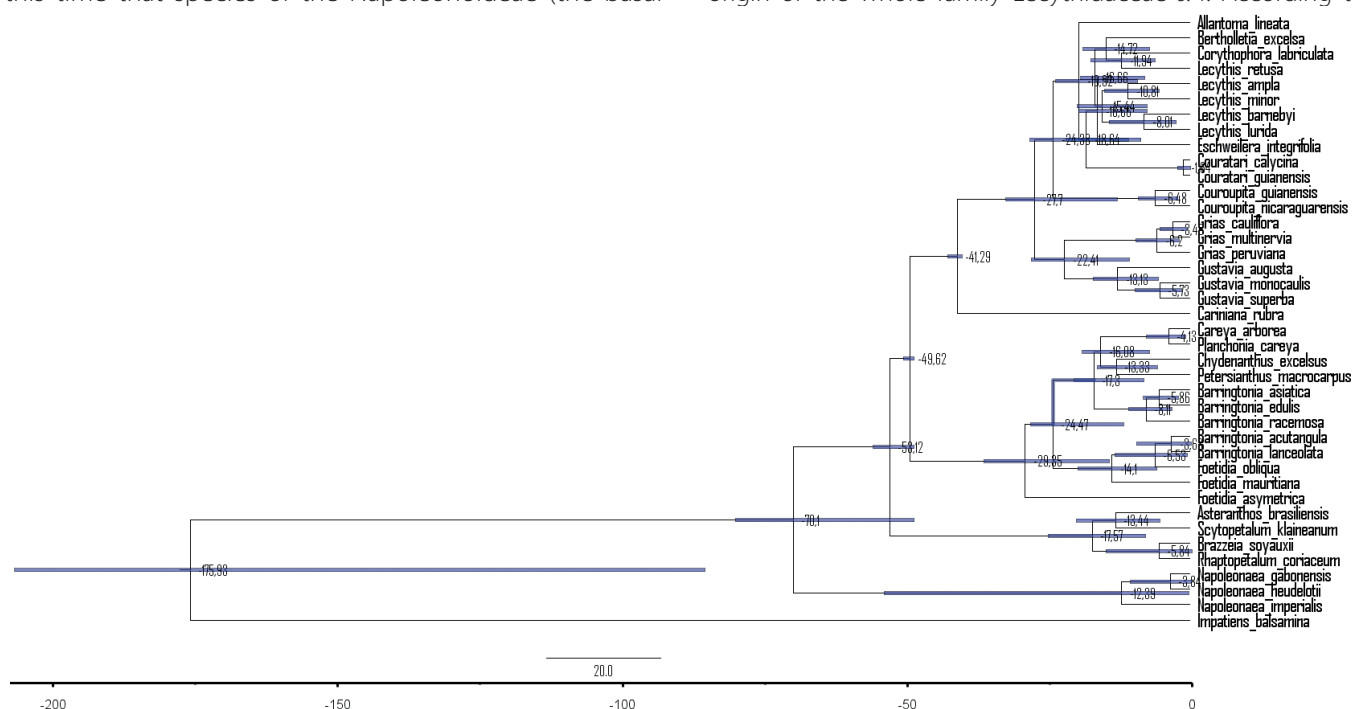
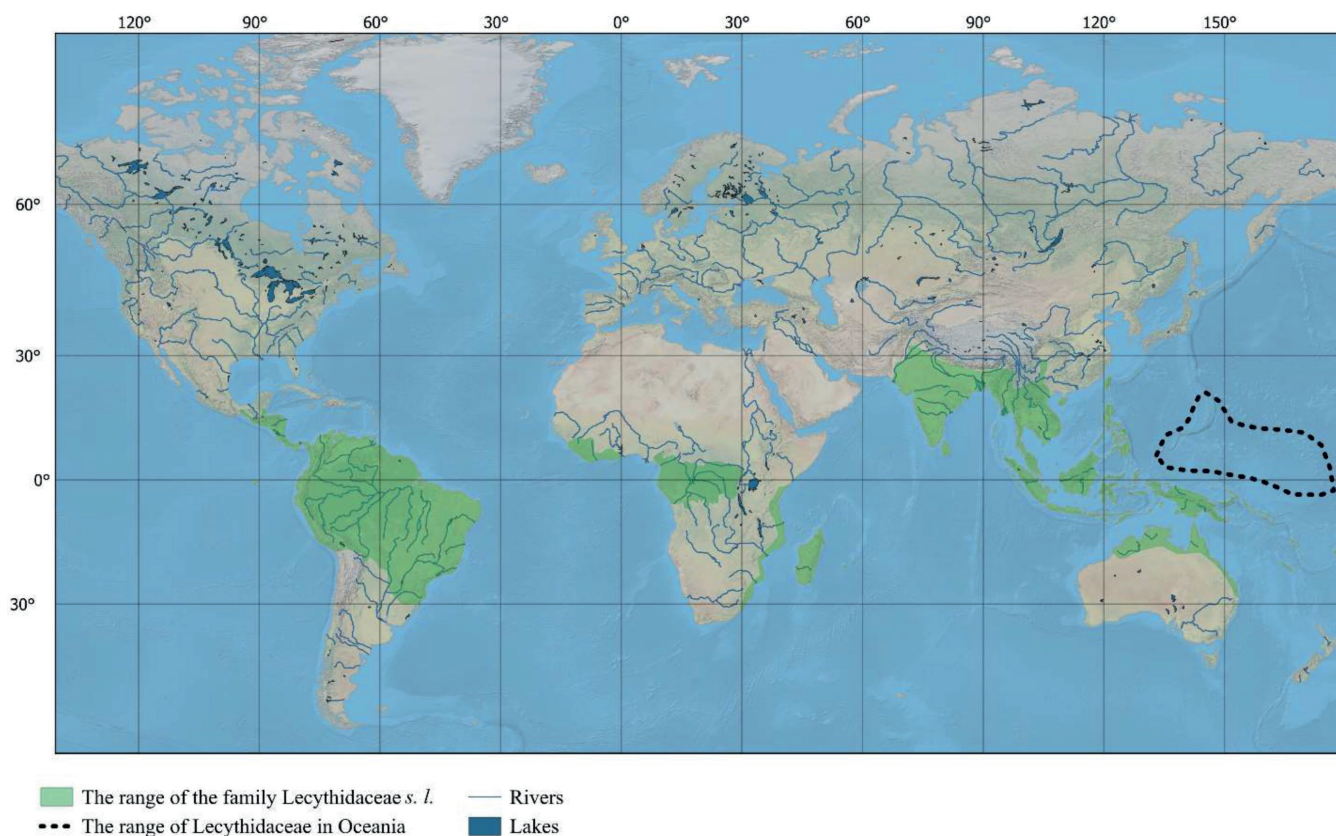


Fig. 2. Calibrated cladogram of *Lecythidaceae* s. l.



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Fig. 3. Modern distribution of *Lecythidaceae s. l.*

paleobotanical data of *Barringtonioxylon* wood, dated to the Late Cretaceous and anatomically similar to the wood of all species of the family, the Late Cretaceous period could be considered the starting point for the further processes of distribution of *Lecythidaceae s. l.* taxa.

The subfamily closest to Napoleonoideae, based on the results of the model, is Scyttopetaloideae. All of its species, with the exception of *Asteranthos brasiliensis*, also grow in the Guinea-Congo floristic region. So, *Rhaptopetalum coriaceum* inhabits the coast of the Gulf of Guinea, primarily in its western part, within the Congo basin [PoWO]. *Scyttopetalum klaineianum* is distributed even more locally and is found only in Gabon, Congo, Cameroon, and Equatorial Guinea [PoWO]. *Brazzeia soyauxii* is distributed in the eastern and southern parts of the Guinea-Congo region [Takhtadzhyan 1978; PoWO], reaching the savannas. *Asteranthos brasiliensis* is the only species from the subfamily Scyttopetaloideae reached South America [PoWO], particularly the Central Amazon region (Fig. 4). Based on calibration data, this happened approximately 17 million years ago. The dispersal was by long-distance transport, i.e., anemochorous or animal disseminators. Paleobotanical data allow to suggest that this was a secondary colonization of South America by species of *Lecythidaceae s. l.*

The way to the east of *Lecythidaceae* was possibly difficult. Based on the results of a calibrated cladogram, this process may have begun approximately 50 million years ago. It was associated with the dispersal of species of the subfamily Barringtonioideae into Asia (Fig. 5).

The first two clades of this subfamily are represented only by *Barringtonia*. These mostly coastal ("peri-mangrove") plants began to spread eastward, colonizing large areas along the east coast of Africa. The range of *Barringtonia racemosa* covers East African coast from southern Kenya to northern South Africa, while *Barringtonia asiatica* spreads to eastern Tanzania, from where it reached Madagascar [PoWO]. Further, through Hindustan, the species of the genus *Barringtonia* reached

Asia, where they became extremely widespread. Their range is bordered in the north by Himalayas, so their further path was to the east. Then they reached Indochina and Malesia. *Barringtonia acutangula* and *Barringtonia lanceolata* also grow there. Then species of the genus colonized Northern Australia, spreading along its coast in the Cape York and Arnhem Land peninsulas, where *B. racemosa*, *B. asiatica*, and *B. acutangula* also grow nowadays [PoWO]. Finally, the genus *Barringtonia* reached Melanesia (*B. edulis*).

Species of another clade of the subfamily Barringtonioideae diverged much later, but still in Africa, about 17 million years ago. The range of the most basal genus in this clade, *Petersianthus*, consists of two parts. *Petersianthus macrocarpus*, separated from the main Barringtonioideae tracks, returned (or initially did not leave) to the Guinea-Congo region [Takhtadzhyan 1978] and spread there. Another species, *P. quadrialatus*, with other ones, reached Asia and further spread to the Philippines. Other taxa of the subfamily followed the main tracks. Species of the genus *Careya* (in particular, *C. arborea*) dispersed throughout Hindustan and Indochina. The genus *Chydenanthus* has a similar range, with the only exception that it is absent from Hindustan, but is widespread in Malesia (in particular, *Chydenanthus excelsus*) [PoWO]. The genus *Planchonia* dispersed throughout Malesia and, like some *Barringtonia* species, also reached Northern Australia.

Species of the subfamily Foetidioideae diverged from Barringtonioideae while they had not yet left Africa, approximately 29 million years ago. They remained on the East African coast, also reaching Madagascar and the Mascarene Islands, forming an isolated East African-Madagascar relict lineage. *Foetidia obliqua* occupies a small area of the Tanzanian coast and is also distributed in Madagascar, like *Foetidia asymetrica*. *Foetidia mauritiana*, however, is found only in the Mascarene Islands [PoWO].

Finally, another stage of the dispersal of *Lecythidaceae s. l.* is associated with their first entry into South America (Fig. 6).

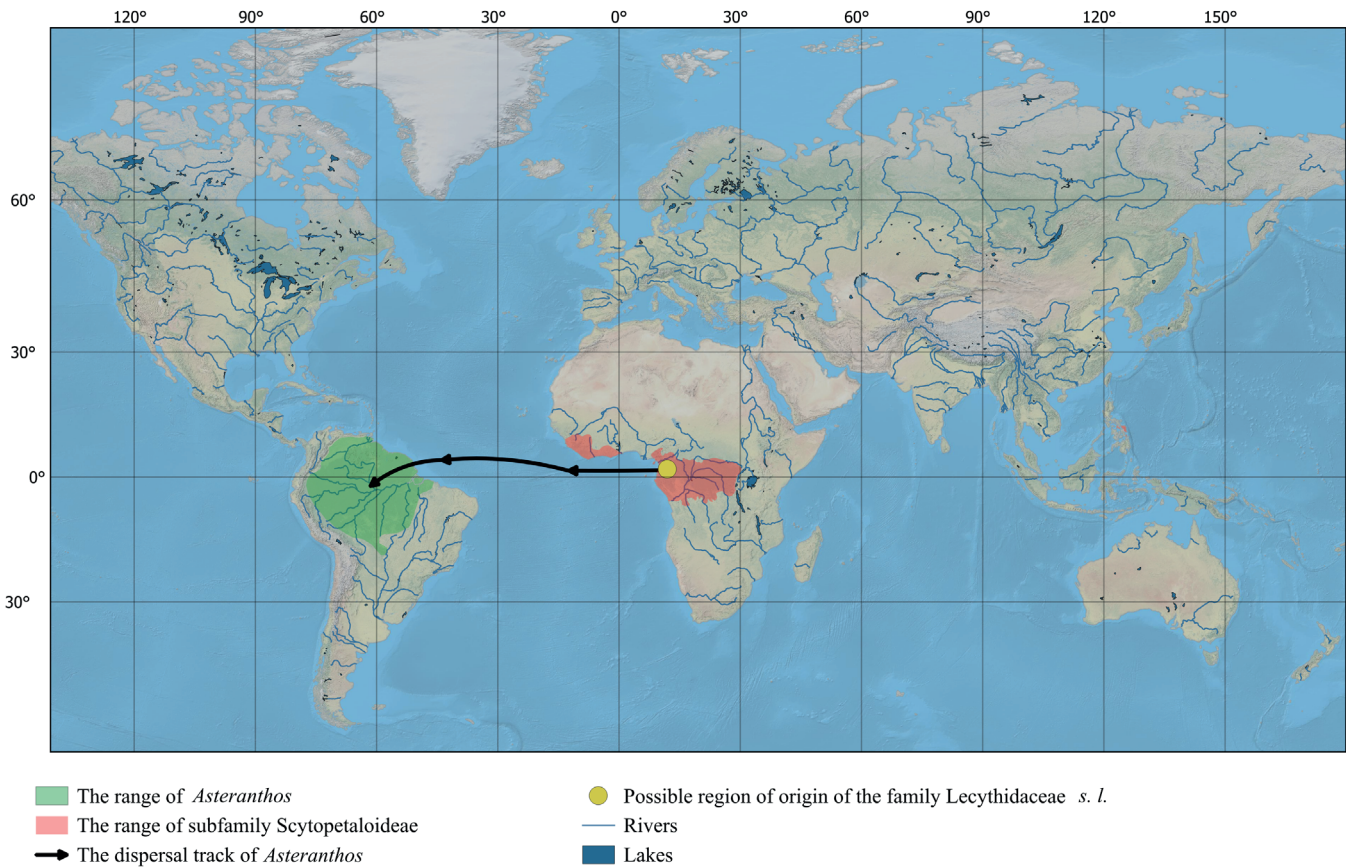


Fig. 4. Track of Scytopetaloidae to South America

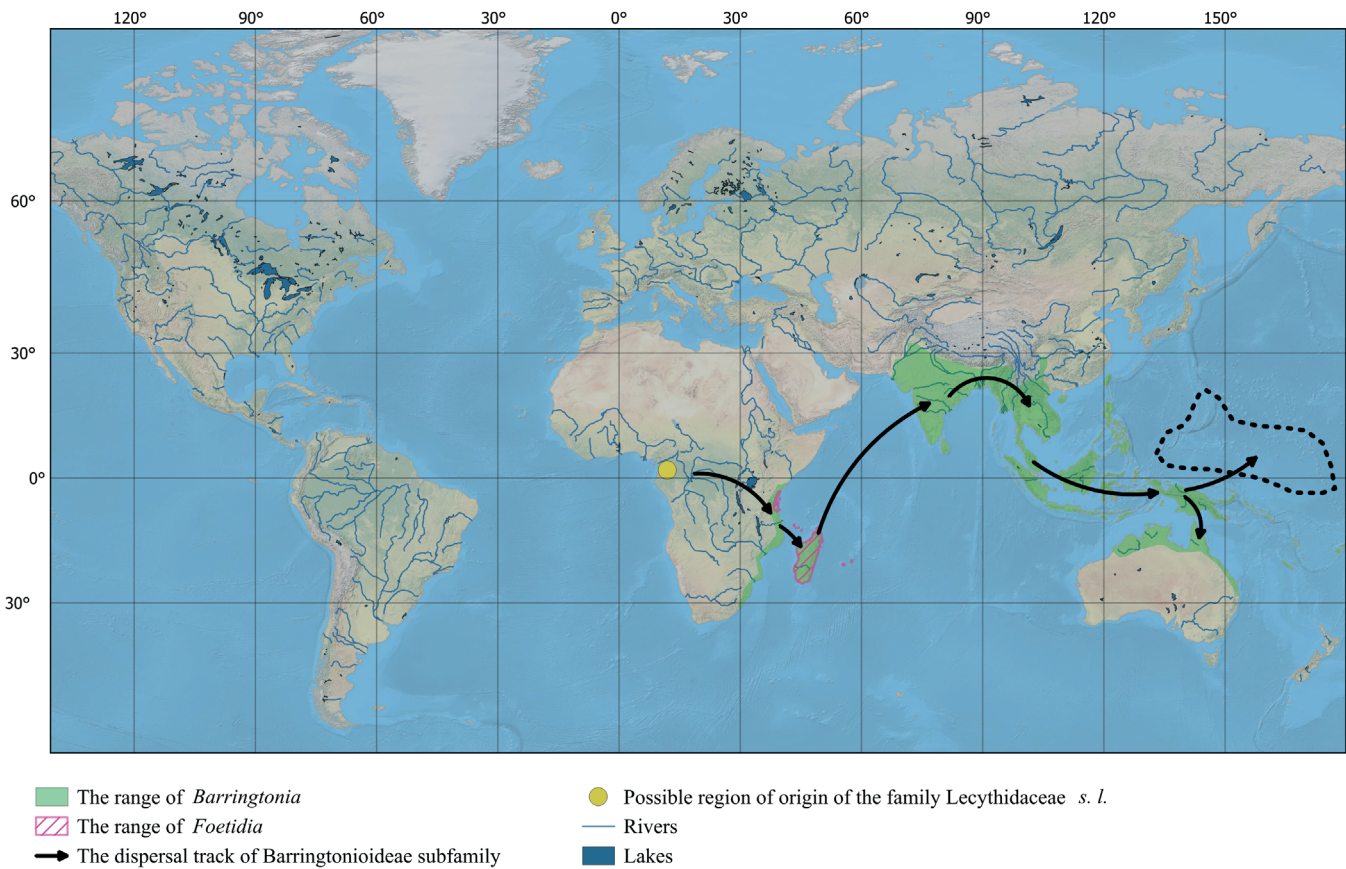
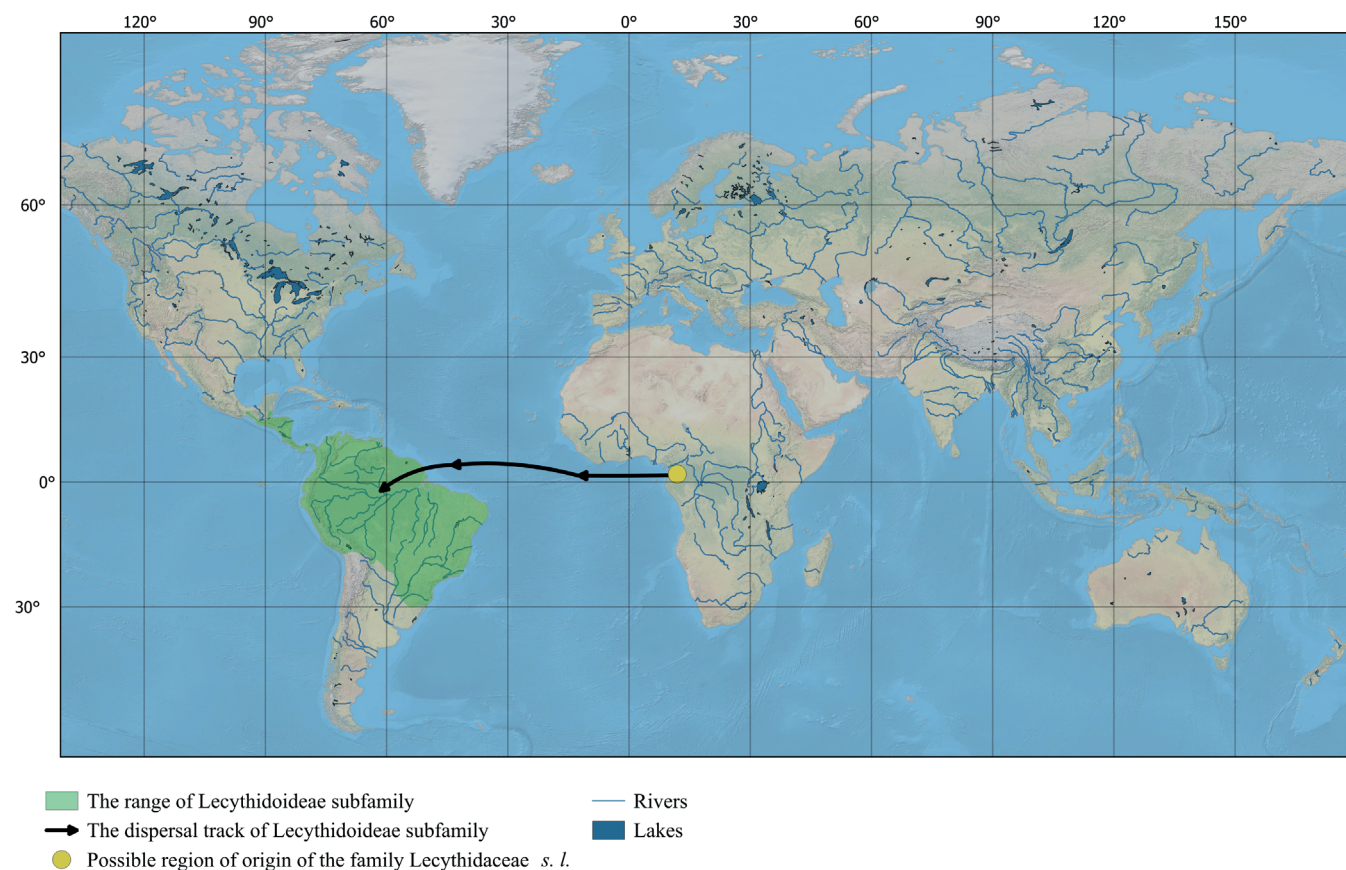


Fig. 5. Tracks of Barringtonioideae



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Fig. 6. Tracks of Lecythidoideae to South America

Based on the results of the calibrated cladogram, these events also began approximately 50 million years ago. Species of the Neotropical clade, which includes *Grias* and *Gustavia*, possibly were the first to complete this way, reaching the territory of the modern Brazilian Highlands and moving further west. *Grias* species dispersed mostly in mountainous regions, primarily in the Northern Andes (*Grias peruviana*), as well as in northern Amazonia (*Grias multinervia*) and Central America (*Grias multinervia*, *Grias cauliflora*). Species of the genus *Gustavia* have spread extremely widely, both in Central America (*Gustavia monocalis*, *Gustavia superba*), the region of the Guiana Highlands and Amazonia (*Gustavia augusta*) and in the Northern Andes [PoWO].

Species of the genus *Couroupita*, another Neotropical clade, also have a wide distribution. They inhabited both mountainous and lowland regions. Specifically, *Couroupita nicaraguensis* grows in the mountainous regions of Central America and extends into the northern Andes. *Couroupita guianensis* has an extremely wide range, covering territories from Central America to the southern borders of the Amazon basin [PoWO].

Genera included in another Neotropical clade covered large areas in the Guiana Highlands (*Couratari calycina*, *Couratari guianensis*), but some reached regions of Central Amazonia (*Allantoma lineata*). Others (*Cariniana rubra*) remained in the Brazilian Highlands and became among the few that colonized the steppe landscapes of the cerrado.

Finally, species of the “last” Neotropical clade adapted to a variety of environmental conditions. Some species colonized the mountainous regions of Central America and the Northern Andes (*Eschweilera integrifolia*). Others spread

widely across the Amazonian tropical rainforests (*Lecythis retusa*, *Lecythis barnebyi*). Others colonized the steppe areas of the cerrado (*Lecythis lurida*). And many went far north, reaching the Yucatan Peninsula (*Lecythis ampla*, *Lecythis minor*).

CONCLUSIONS

The family Lecythidaceae s. l. hypothetically originated in Central Africa, where species of the basal subfamily Napoleonoideae grow. The family originated approximately 85 million years ago.

The first colonization of South America probably happened about 50 million years ago by species of the subfamily Lecythidoideae, which later spread extremely widely throughout the tropics of the New World.

The eastward dispersal of subfamily Barringtonioideae species from Africa also began 50 million years ago and followed several routes. Initially, species of the subfamily occupied large areas along the coast of East Africa, and then moved into Asia through Hindustan and Indochina peninsulas, spreading to Malesia, northern Australia, and Oceania.

Species of the subfamily Scyttopetaloideae diverged at the earliest stages of the family’s evolution, but dispersed beyond the region of its origin much later (about 17 million years ago): the only Neotropical species of the subfamily, *Asteranthos brasiliensis*, grows in Central Amazonia.

The dispersal of the subfamily Foetidioideae, the most recently diverged group, happened approximately 25±10 million years ago in East Africa, with the single genus *Foetidia* that reached Madagascar and the Mascarene Islands. ■

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THE RADIATION RECONSTRUCTION MODEL (VERSION 2) AND ITS APPLICATION FOR ESTIMATING VARIABILITY OF ULTRAVIOLET RADIATION OVER THE 1968–2024 PERIOD IN MOSCOW

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ABSTRACT. Solar radiation is a vital component of the climate system, and knowledge of its temporal variation is of great importance. Ultraviolet (UV) radiation, due to its high photon energy, has a strong impact on the biosphere and human health. In this work, a reconstruction model (version 2) for estimating surface solar radiation long-term variability was proposed. It has been configured to assess the variability of erythemal UV radiation and UV-A radiation within the 315–400 nm spectral range. In this version of the model, physical parameterizations of UV radiation with respect to various factors have been refined, and an additional factor, which accounts for nitrogen dioxide influence on UV radiation, has been added. The model was validated against long-term UV measurements at the Moscow State University Meteorological Observatory, which has the longest continuous record of UV observations in the world. The mean RMSE of the differences between model simulations and measurements is on the order of 3% for annual values, which is comparable to the measurement uncertainty. High correlation coefficients (about 0.8) were observed between the modeled and measured values of the UV temporal variability for almost all periods. The analysis of surface UV radiation variability for the 1968–2024 period revealed noticeable UV fluctuations, which were characterized by a minimum in the late 1970s and early 1980s and a maximum after 2010. For erythemal UV radiation, the maximum amplitude of annual changes is about 30%, and for UV-A radiation it is about 19%. Much stronger changes were observed for erythemal UV radiation compared to UV-A radiation owing to the additional influence of ozone variability.

KEYWORDS: Reconstruction model, UV radiation, ozone, aerosol, cloudiness, long-term UV series

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INTRODUCTION

Solar radiation (SR) is an important component of the thermal balance, influencing the geographical distribution of the climatic resources of our planet. Ultraviolet radiation (UVR, 10–400 nm), despite its small energy fraction in the spectrum of solar radiation at the Earth's surface (about 5–10%), has a pronounced biological effect, especially in the UV-B region (280–315 nm), due to the increase in photon energy with decreasing wavelength.

Surface solar energy experiences noticeable seasonal and interannual variations due to the influence of various factors (Liou 2010, WMO 2007). The most important factors are the astronomical ones, mainly a solar angle above the horizon. Geophysical factors also have a significant impact on SR. Depending on the spectral range, gas absorption of solar radiation may play an important role. In the UV range of the spectrum, there are strong absorption bands of ozone. In addition, some other gases (nitrogen dioxide, sulfur dioxide, and a number of

organic gas species) also have absorption bands there. In the visible range, relatively weak absorption by ozone and nitrogen dioxide is observed. The infrared spectral region is characterized by strong water vapor absorption bands, as well as by the absorption of a number of other gases like CO₂, CH₄, and others (Timofeev and Vasiliev 2003). At the same time, the content of the number of gases in the atmosphere is low, and their effect on the actual attenuation of solar radiation may be negligible.

Atmospheric aerosol also has a significant effect on the attenuation of solar radiation. Its properties can exhibit noticeable temporal and spatial variability, especially over recent decades (Zhang et al. 2025). Noticeable changes in aerosol content with a pronounced negative trend have been observed in the Moscow region (Poliukhov et al. 2024). The influence of this factor is particularly pronounced in the UV range of the spectrum due to the prevailing fine aerosol fraction, which increases aerosol optical thickness at shorter wavelengths.

Cloud cover is one of the most important factors affecting solar radiation. Its optical properties are determined by cloud particle size distribution and their aggregate state. Optically thin ice clouds of the upper layer have a weak effect on radiation, while clouds of the lower level noticeably attenuate SR (Abakumova et al. 2008, Calbo et al. 2005). The cloud amount and their spatial structure also play a noticeable role (Chubarova 1998).

Solar radiation has experienced significant interannual changes in the 20th and 21st centuries. Thus, according to the results of global monitoring, a noticeable decrease in surface SR was revealed approximately in the middle of the twentieth century, which was replaced by its growth since the early 1980s (Ohmura 2009, Wild 2009, Long et al. 2009, Wild 2012, Sanchez-Lorenzo et al. 2015, Wild 2016). Since the early 1990s, solar radiation over the European plain has also shown a weak but significant upward trend (The third assessment report 2022, Gorbarenko 2016, Volpert, Chubarova 2021). The causes of these phenomena are mainly related to temporal variations in cloud amount (Abakumova et al. 1996, Stjern et al. 2009, Liepert et al. 2002, Volpert, Chubarova 2021, Gorbarenko 2020, Gorbarenko 2022), variations in atmospheric aerosol (Streets et al., 2009, Wang et al., 2009, Volpert, Chubarova 2021), and gas composition, especially ozone for the UV-B spectral region (Chubarova, Nezval 2000). The indirect influence of cloud-aerosol effects may also be important (Lohmann and Feichter 2005).

Notable long-term trends have also been observed for surface UV radiation (Krzyściński et al. 2025, den Outer et al. 2010, Čížková, K. et al. 2018, McKenzie et al. 1999, etc.). It should be noted that spatial and temporal variations in UV radiation near the Earth's surface are very significant due to strong variations in geophysical parameters (Wang et al. 2013, Zubov et al. 2025). In addition to the ozone reduction, the decreases in cloud amount and aerosol loading play a significant role in the positive trends of UV radiation observed after the mid-1990s over northern mid-latitudes (Bais et al. 2014).

In order to quantify the interannual changes in surface SR and UVR in different geographical conditions, different reconstruction models are usually used (Kaurola et al. 2000, Krzyściński et al. 2004, Chubarova 2008, Lindfors et al. 2007, etc.). Reconstruction models are the tools that are applied to assess the long-term variability in SR and UVR when direct measurements are unavailable. These models have evolved from simple empirical formulas to the complex account of the physical processes, with additional use of reanalysis data. With the help of these models, it is possible to estimate the influence of a particular geophysical factor and quantify its contribution to the variability of solar radiation.

For example, the most advanced studies of long-term UVR trends (WMO 2007) rely on these reconstructed datasets, which allow separation of the effects of ozone depletion and assess the effects of cloud and aerosol variability on ultraviolet radiation near the surface (WMO 2007, Herman 2010). These models have played a crucial role in assessing long-term trends in UV radiation and identifying their causes. However, not all geophysical factors were taken into account in these models, and some of the dependencies have to be improved. Note that modern machine learning methods, with their high efficiency, do not allow such analyses to be done.

In this paper, an improved version of the reconstruction model is proposed, which has been configured for the evaluation of surface UV radiation changes, taking into account new factors and refining previously

obtained parameterizations in the first version of the UV reconstruction model, presented in (Chubarova 2008). This version of the model can also be used for other spectral ranges after appropriate additional correction. The emphasis on the study of UV radiation is related to its strong influence on the biosphere and the connection of UV radiation with climate change (Bernhard et al. 2023, Barnes et al. 2022). The assessment of long-term changes in UV radiation is especially important, since many biological and health effects depend on the dose of ultraviolet radiation accumulated over a long period. Therefore, the assessment of possible UV changes in previous decades is very essential.

DATA AND METHOD DESCRIPTION

The development of the new version of the UV reconstruction model was based on the results of model calculations and some parameters retrieved from the UV measurements at the Moscow State University Meteorological Observatory (MSU MO) (55.7°N, 37.5°E).

For calculations, the TUV (Tropospheric Ultraviolet Visible) radiation model with the 8-stream discrete ordinate method (Madronich and Flocke 1998) was applied in the study. This radiative model produces the smallest errors in calculating UV radiation (less than one percent). The radiative simulations were performed in the range of 280–400 nm with a resolution of 1 nm. The vertical distribution of the model included 80 layers at 1 km resolution. We used model simulations mainly for the estimation of several physical parameters, which cannot be obtained from measurements.

Various datasets were applied as the input parameters for the reconstruction model. In particular, the data of total ozone content from the Central Aerological Observatory (CAO) available via the archive of the Voeikov Main Geophysical Observatory (VMGO) were used to assess ozone content before 1979, and for the later period, the NASA satellite measurements (TOMS, EARTH Probe, OMI) were used. In the absence of satellite measurements during the 1993–1996 period, we again used the ground-based ozone data from the CAO. Studies have shown that the differences between satellite and ground-based measurements lie within a few percent (Piacentini et al. 2002), which is satisfactory accuracy for their application in the reconstruction model.

For characterizing the aerosol attenuation, the aerosol optical thickness (AOT) at 340 nm was applied. These data were available from the AERONET data at Moscow State University for the 2002–2021 period. For other periods, we converted the estimates of AOT at 550 nm from the measurements of direct short-wave radiation and atmospheric moisture content (Tarasova, Yarkho 1991) to AOT at 340 nm using the climatic values of the Angstrom parameter from AERONET climatology in Moscow. It should be noted that there is a satisfactory agreement between the values of aerosol optical thickness in the visible range of the spectrum obtained from direct AERONET measurements and the AOT values calculated using the method described in (Tarasova, Yarkho 1991).

Satellite data on NO₂ content measured by the OMI instrument (Burrows et al. 1998) were used to account for the effects of nitrogen dioxide on UV radiation. In the analysis, the period from 2005 to 2024 was considered, as no reliable NO₂ data were available before that time. When calculating for longer periods, it was assumed that NO₂ values for the previous period corresponded to the mean values observed in 2005 and 2006, and they did not change.

Such an approach is justified because restrictions on gasoline quality in Moscow were introduced only in 2005. It should be noted that accounting for the NO_2 content is especially important in urban conditions similar to those of the Moscow metropolitan area, where its concentrations are relatively high.

The values of the spatial surface albedo, A , were also used as an input parameter in the model. In the UV region, it was set to 0.02 for the warm period, and for the cold snow period, this value was assumed to be 0.4. This is lower than the local snow surface albedo due to the influence of dark trees and buildings, in accordance with the TOMS MLER data (Chubarova et al. 2002). During the transition periods, we applied the degree of snow coverage coefficient, which is a standard characteristic measured at meteorological stations.

For obtaining the data on cloud amount, we used hourly visual cloud observations at the MSU MO for the 1968–2024 period. UV cloud transmission at different cloud amounts was estimated from long-wave UV measurements (Chubarova 1998). To simulate the UV effects due to cloud optical thickness (COT), the hourly measurements of global shortwave radiation in the absence of direct radiation were used with the additional correction for the UV spectral region.

Validation of the UV reconstruction model was carried out using long-wave UV observations since 1968 at the MSU MO (Chubarova, Nezval 2000), which are the longest series of UV radiation measurements in the world. The long-wave UV measurements were carried out using UV pyranometers (Vysotsky et al. 1982) and some other instruments, which were calibrated for the same 300–380 nm spectral region. However, this is not a standard spectral range. Therefore, for this study, the measurements were converted to the standard UV-A region (315–400 nm). For this purpose, the parameterization has been obtained, based on TUV model simulations in both the 300–380 nm and 315–400 nm spectral regions with different geophysical input parameters. Additionally, we compared the obtained results with the direct evaluation of the difference between UV radiation within the 300–380 nm and 315–400 nm ranges during the international UV Filter Radiometer comparison 2017 campaign at the PMOD/WRC, Switzerland in 2017 (Hülsen, Gröbner 2018). The two dependencies show good agreement with a difference of approximately 2%. The entire dataset before 2021 was corrected, using the obtained parameterization. Since 2021, direct UV-A observations have been a part of measurements of a new radiation RAD-MSU (BSRN) complex, which has been in operation at the MSU MO. As a result, for the 1968–2024 period, the long-term homogeneous series of UV-A radiation measurements were obtained.

The results of the model reconstruction of erythral UV radiation (U_{Very}) were also tested. Erythral UV radiation is a biologically active UV radiation that causes erythema (skin redness) and is characterized by a specific spectral erythral sensitivity. Testing the quality of U_{Very} reconstruction has been carried out since 1999, when regular measurements of erythral UV radiation began at Moscow State University (Chubarova 2002, Zhdanova et al. 2014). Since 2021, erythral UV radiation has been measured as a part of the monitoring program of the new radiative RAD-MSU (BSRN) complex. The entire U_{Very} dataset has been calibrated against the instrument, which was in turn tested during the international UV Filter Radiometer comparison in 2017 at the PMOD/WRC, Switzerland. Hourly U_{Very} data were corrected for solar elevation and ozone according to the standard procedure

(Hülsen, Gröbner 2018). In addition, the quality of UV measurements was tested by comparisons with model estimations in clear sky conditions. The analysis has shown a satisfactory agreement between measurements and model data.

RESULTS

Description of the UV radiation reconstruction model

The proposed reconstruction model is intended to assess the long-term variability of surface solar radiation due to various geophysical factors. The version of the model is a further development of the UV reconstruction model described in Chubarova (2008), however, the new version includes new factors, refinements, and new physical parameterizations. An additive approach is used, in which the effect of each factor is assessed separately with the exception of those, which assessment requires accounting for mutual influence.

The interannual variability of solar UV radiation (V) per month, season, or year can be written as the sum of UV relative changes caused by variations in total ozone content ($v1$), changes in nitrogen dioxide content ($v2$), variations in aerosol optical thickness ($v3$), changes in UV transmission due to cloud cover ($v4$), and variations in cloud optical thickness ($v5$) as shown in Eq. (1):

$$V_i = \sum_j [W_j(h) (v1_{i,j}([O3]) + v2_{i,j}([NO2]) + v3_{i,j}(AOT, P_{clear}) + v4(CQ, A) + v5_{i,j}(OT, P_{ov}, A))] I \sum_j W_j(h) \quad (1)$$

where the index i corresponds to the year number, and the index j corresponds to the month number; $[O3]$ is the total ozone content; $[NO2]$ is the nitrogen dioxide content; AOT and OT are the optical thickness of aerosols and clouds; P_{clear} and P_{ov} are the frequencies of clear and cloudy days; CQ is the cloud UV transmission for different cloud amounts; and A is the spatial surface albedo.

The equation also takes into account the weighting function W_j , which has a power-law relationship with solar angle $W_j(h) = h^b$, where b is the coefficient obtained from model calculations; it decreases with increasing wavelength. According to model simulations for erythral UV radiation, $b = 2$, and for UV-A radiation, $b = 1.3$. In the further analysis, the influence of each geophysical factor in the new model version will be described.

The effect of total ozone on UV

The relative changes of UV radiation (dQ_{oz}/Q_{oz_mean}) against its mean value to variations in total ozone content against its mean value $d[O3]/[O3_{mean}]$, $v1$, are estimated by taking into account the radiation amplification factor $Rx(h)$, which depends on the solar angle h and spectral range considered (Eq. 2):

$$v1_{i,j} = \frac{dQ_{oz_{i,j}}}{Q_{oz_mean}} = Rx(h^j) \left[\frac{d[O3]_{i,j}}{[O3]_{mean}} \right] \quad (2)$$

For erythral UV radiation at $h = 40^\circ$, $Rx(h)$ is -1.1, which is consistent with Andradý et al. (2010). However, due to the shift of the effective wavelength with a change in solar angle, this value may noticeably vary. Therefore, the new version of the model takes into account the Rx dependence

on solar angle. The following parameterization was estimated using modeling for the range $h = 5-90^\circ$ (Eq. 3):

$$Rx(h) = -0.0000019 h^3 + 0.000387 h^2 - 0.0246h - 0.68305, R^2 = 0.997 \quad (3)$$

For the UV-A region, the Rx value is small ($Rx_{UV-A} = -0.02$), because ozone absorption is very weak there.

The application of Rx dependence on solar angle significantly changed the estimation of UVery variability due to ozone during winter months, when solar angle is small. For example, in December, the estimated UVery variability due to ozone has changed by up to 6% compared to the previous version of the model due to changing Rx from -1.1 to -0.89 at a solar angle of about 10° . For annual values, the difference of UVery variability was within 1% compared to the first version of the model.

Overall, the ozone factor contributed to maximum UVery annual variations of up to 15% for the 1968–2024 period with a standard deviation of 3.5%. For UV-A radiation, the ozone effect is very small with a maximum annual variability of up to 0.2%.

The effect of nitrogen dioxide on UV

The account of nitrogen dioxide [NO_2] influence on UV radiation (v_2) was carried out according to the model dependence of relative UV sensitivity to changes in NO_2 content per 1 matm.cm obtained in (Chubarova 2006). Using this relative UV sensitivity, we can estimate $v_{2,ij}$ (Eq. 4):

$$v_{2,ij} = \frac{dQNO_{2,ij}}{QNO_{2,mean}} = [NO_2]_i (A \times \ln(h_j) - B) - [NO_2]_{mean} (A \times \ln(h_j) - B), R^2 = 0.99 \quad (4)$$

According to the model calculations, the coefficients A and B for UVery are equal to $A = 0.0083$ and $B = 0.0431$, respectively, while for the UV-A region, these coefficients are the following: $A = 0.0138$ and $B = 0.074$. The difference in the A coefficients demonstrates a stronger UV-A dependence on NO_2 content. This happens since there is an increase in NO_2 absorption coefficients with wavelength in the UV range. Similarly, the influence of other small gas species with absorption bands in the UV range, such as SO_2 , $HCHO$, etc., can be accounted for by using a similar scheme. However, their concentrations in Moscow are very low and do not have a significant impact on the interannual UV variations, while the influence of NO_2 on UV in urban environments can be noticeable.

According to the satellite OMI data, the mean NO_2 content during the 2005–2024 period was equal to 0.57 matm.cm and was characterized by a noticeable negative linear trend of 0.05 matm.cm per 10 years (with correlation coefficient $r = 0.68$). The observed NO_2 variations led to small annual changes of 0.2% in erythemal UV radiation and of 0.4% in UV-A radiation. However, for winter months with low solar angles, the effects are more pronounced. For example, in December, variations reach 0.5% and 0.8%, respectively, for UVery and UV-A radiation. Despite the noticeable negative trend in NO_2 content, these changes have a limited impact on the temporal fluctuations of UV radiation in Moscow.

The effect of aerosol on UV

The relative changes in UV radiation due to aerosols (v_3) were estimated with a new scheme, taking into account the effects of surface albedo and a more accurate assessment of aerosol attenuation. These values were calculated using the parameterization obtained from accurate model

simulations with account of AOT, single scattering albedo $SSA = 0.92$, Angstrom parameter a , and solar angle h as well as the frequency of days during a month, when it is possible to estimate AOT (P_{clear}). The parameterization is the following (Eq. 5):

$$v_{3,ij} = \frac{P_{clear,ij} dQ_{aer,ij}}{Q_{aer,mean}} = P_{clear,ij} \left(AOT_{550,ij} \left(\frac{550}{340} \right)^{a'} - AOT_{550,mean,ij} \left(\frac{550}{340} \right)^{a'} \right) \left(\left(0.42 \frac{1}{\sinh_j} + 0.93 \right) SSA + \left(-0.49 \frac{1}{\sinh_j} - 0.97 \right) \right), R^2 = 0.99$$

Note that in summer, mean P_{clear} is equal to 47%, while in some years, it can reach 97%. In winter, mean P_{clear} is only 10% with the maximum of 53% in some years. The decrease in this frequency in winter leads to a much smaller effect of aerosol.

The new aerosol scheme in the reconstruction model has significantly changed the assessment of its impact on UV radiation since the old scheme used only an empirical relationship between UV radiation and aerosol optical thickness. The maximum UV variability due to aerosols reaches only 3%, with a standard deviation of 0.6%. The application of the new aerosol scheme provided a slightly reduced positive UV trend compared to the old aerosol scheme. However, the overall trend of increasing UV radiation in recent years due to the decrease in aerosol has not been affected. This negative AOT trend has been revealed according to the AERONET measurements during the recent decades (Poliukhov et al. 2023).

The effect of cloud amount on UV

The UV variability due to cloud amount (v_4) was obtained by using the estimates of effective UV cloud transmittance. First, this characteristic at zero albedo ($A=0$) was calculated as $CQ_{A=0} = Q/Q_0$, where Q is the global UV radiation in the presence of clouds, and Q_0 is the UV radiation in their absence at the same other parameters and zero surface albedo.

The $CQ_{A=0}$ is defined as a combination of relative cloud amount frequency, weighted by the cloud transmittance in the UV range (Eq. 6):

$$CQ_{A=0} = \sum_{NI=0}^{10} (\{ P(NI) - P(NI, N=10) \}) \frac{CQ_{A=0}(NI) + P(NI, N=10)}{CQ_{A=0}(NI) CQ_{up}} \quad (6)$$

Here, $P(NI)$ is the frequency of the most dense lower-level cloud amount NI at different total cloud cover amounts N for a given month; $P(NI, N=10)$ is the frequency of total cloud amount $N = 10$ when lower-level cloud amount is different. The UV transmittance at different lower-level cloud amount $CQ_{A=0}(NI)$ and at overcast upper-level clouds are determined according to long-term measurements (Chubarova 1998). This equation is based on the assumption that upper- and middle-level clouds affect the UV transmittance only when $N = 10$. Hence, this method independently considers the UV transmittance by optically dense lower-level clouds and thin upper-level clouds.

When the surface albedo is high, the effects of multiple reflection between the surface and the atmosphere should be taken into account.

For cloudy conditions, the multiple reflection coefficient R is defined as follows (Eq. 7):

$$R = r0(1 - N) + N \times (r0 + k \times OT) \quad (7)$$

Here, $r0$ is the coefficient of multiple reflection between a surface with different albedo and a cloudless atmosphere, N is the cloud amount, and OT is the cloud optical thickness. The efficiency of multiple reflection in a cloudy atmosphere is determined by the coefficient k . According to model calculations, this value is equal to 0.58.

The coefficient of multiple reflection in clear sky conditions, $r0$, is determined by the properties of the atmosphere and has different relationships with various atmospheric parameters, depending on the spectral range. According to model calculations for UV-A radiation, the coefficient of multiple reflection, $r0$, is determined by AOT at 550 nm, while for erythral radiation $r0$ is determined by the total ozone content [O3].

Based on model calculations, the following parameterizations of the $r0$ coefficients for UVery and UV-A radiation are as follows (Eqs. 8–9):

$$r0(UVery) = -0.000081 \times [O3] + 0.39667, R^2 = 0.93 \quad (8)$$

$$r0(UV-A) = 0.0247AOT550 + 0.3124, R^2 = 0.94 \quad (9)$$

The multiple reflection coefficient R in cloudy conditions is assumed to be proportional to the radiative loss due to clouds (Eq. 10):

$$R = r0 + k(1 - CQ_{A=0}) \quad (10)$$

Accordingly, we represent UV radiation at surface albedo A for cloudless and cloudy conditions as Eqs. 11–12:

$$Q_A = Q_{A=0} / (1 - r0A) \quad (11)$$

$$Q_A = Q_{A=0} / (1 - RA) \quad (12)$$

As a result, the UV cloud transmittance at surface albedo A can be estimated as Eq. 13:

$$CQ_A = CQ_{A=0} (1 - Ar0) / (1 - A(r0 + k(1 - CQ_{A=0}))) \quad (13)$$

The CQ_A value is used in the calculation of UV variability due to UV cloud transmission $v4_{ij}$ (Eq. 14):

$$v4_{i,j} = \frac{dCQ_{Ai,j}}{CQ_A \text{ mean}} \quad (14)$$

This updated scheme for estimating UV variability due to cloud amount at different surface albedo also led to the changes with a maximum range of 0.6% compared to the old scheme. The spectral features of R also have an impact on the difference in the changes of UVery and UV-A radiation due to different types of dependencies for $r0$ (see Eq. 8 and Eq. 9). The range of variability lies within 3.2% for annual values. However, for the summer period, when

surface albedo does not change, the range of variability is significantly lower, approximately 1.8%.

Overall, cloud amount is one of the most significant factors affecting the interannual variability of solar radiation. Over the period from 1968 to 2024, the maximum range of UV variability was approximately 18%, with a standard deviation around 4.5%.

The effect of the cloud optical thickness on UV

The radiative attenuation due to the optical thickness of clouds ($v5$) was calculated in conditions of the full absence of direct solar radiation S , i.e., in conditions of a continuous dense extended cloud cover. Variations in effective radius of cloud particles were not taken into account, since they are negligible compared to the effects of cloud optical thickness (Liou 2010). In addition, frequency of cases with optically dense extended cloudiness, Pov , was taken into account. This approach allows a user to estimate the contribution due to variations in cloud optical thickness ($v5_{ij}$) according to Eq. 15:

$$v5_{i,j} = \frac{Pov_{i,j} dCQ_A(S=0)_{i,j}}{CQ_A(S=0) \text{ mean}} \quad (15)$$

In this case, UV cloud transmissions were calculated using cloud transmissions of the entire short-wavelength range, following the previously obtained parameterization (Chubarova et al., 2018).

The use of a new scheme for describing the effect of optically dense clouds compared to the old scheme results in differences of approximately 0.3–0.4%. The maximum interannual differences in UV variability due to this factor are approximately 4%, with a standard deviation of 0.7%. The results of the comparisons between the new and the old model version are presented in Table 1.

The reconstruction model was tested against long-term UV-A measurements for the 1968–2024 period and against UVery measurements for the 1999–2024 period. The assessment of the uncertainties of the UV reconstruction model should account for the existence of the UV measurement errors, which equal approximately 5% according to the instrument certificates¹.

Table 2 shows the estimates of correlation coefficients and RMSE between measurements and model estimates of UV variability. It can be seen that the model generally reproduces relative variability of UV radiation over the years. During the warm season, when the accuracy of input parameters is high, the correlation coefficient between the model and measured values is approximately 0.83. For annual values, the correlation coefficients are slightly lower (0.79 and 0.76, respectively, for UV-A and UVery, see Table 2), which can be attributed to both the increased uncertainty of the albedo effect and the increased measurement errors during the cold season. The mean RMSE estimates are

Table 1. The comparisons of UV relative changes caused by variations in different geophysical factors between the new version 2 and the old model version for UVery and UV-A radiation (given in parentheses), expressed in terms of relative variability (%)

	Ozone impact (v1,%)	NO ₂ impact (v2,%)	Aerosol impact (v3,%)	Effective cloud amount impact (v4,%)	Cloud optical thickness impact (v5,%)
Maximum range of difference	1% (-*)	A new factor	2.5% (2%)	0.6%(0.6%)	0.3% (0.4%)
Standard deviation	0.2% (-*)		0.6% (0.5%)	0.13% (0.14%)	0.06% (0.08%)

Comments: * – since another spectral region was used, hence, the comparison is not meaningful.

¹ <https://www.kippzonen.com/>

approximately 3.1%, which is lower than the measurement errors of approximately 5%.

Therefore, we can conclude that the reconstruction model (version 2) satisfactorily reproduces the interannual variability of UV radiation.

Regarding monthly UV variability, it can be seen that the correlation coefficient significantly increases in the spring and summer months, and the RMSE is approximately equal to the measurement errors. However, in January, the RMSE increases, reaching 11% and 17.9% for UV-A and erythemal UV radiation, respectively. This can be partly attributed to the uncertainties of measurements due to the problems with stability of sensor temperature during the cold season, especially in the first years of measurements, when there were particularly significant differences in erythemal UV radiation. Additionally, the model may not account for the more complex effects of three-dimensional re-reflection in conditions of broken clouds and high surface albedo, which can also contribute to the increase of uncertainty. Nevertheless, the model generally explains more than 60–80% of the observed variability of UV radiation in most months and seasons. It should be noted that only physically determined dependencies have been applied in the model with no additional correction factors.

Variability of surface UV radiation in Moscow according to the reconstruction model

We analyzed the main features in UV variability in the Moscow region using the proposed reconstruction model. Figure 1 shows the interannual variability of annual UV-A and UVery values for the 1968–2024 period. This variability of both UV-A and UVery radiation has revealed a pronounced minimum in the late 1970s and early 1980s, which was followed by an increase that has been decelerating in recent years. The amplitude of UVery variability (around 30%) is significantly higher

than that of UV-A radiation (19%) mainly due to the additional strong influence of ozone on UVery. The differences in the interannual variability between UV-A and UVery radiation vary from -9% to +7%.

The observed UVery trends are in good agreement with the reconstructed UVery data for Central and Eastern Europe (Krzyscin et al. 2004), which also show a significant decrease in the late 1970s and an increase in the 1990s. This confirms the regional nature of the observed variability of UV radiation.

The maximum positive deviation of erythemal UV radiation (+13%) was seen in 2011, when mini ozone holes were observed in spring over northern and eastern Europe (Bernhard et al., 2013) and directly over Moscow. The lower ozone values were also registered in summer. The parallel increase in UV-A radiation in 2011 indicates that this increase was also influenced by other factors, primarily the decrease in cloud cover. This is in agreement with (Bernhard et al. 2013), where it was pointed out that the strong increase in UV in Scandinavian countries was explained by both ozone and cloud decrease. A detailed analysis of the causes of UV variations will be presented in a separate paper. In recent years, after 2011, there has been no significant trend in the erythemal UV radiation. However, the UVery level is approximately 5–8% higher than the average value over the 1968–2024 period.

Fig. 2 presents the interannual variability of UV-A and erythemal UV radiation according to the reconstruction model for the central months of the seasons. One can see different trends in UV radiation for different months of the year. In winter, there is a decrease in UV radiation for both spectral ranges, while in April, July, and October there is a pronounced statistically significant UV increase. The positive trends in April and July are higher for erythemal UV radiation (3–4% per 10 years) compared to UV-A radiation (2% per 10 years).

Fig.3 shows UV variability over the year and over the warm (May–September) period, which demonstrates a consistency of their UV changes. The correlation coefficients

Table 2. The correlation coefficients and Root Mean Square Errors (RMSE) between the results of the UV reconstruction model and measurements for the year, warm season, and central months of the seasons

	Spectral range	Period	Correlation coefficient	RMSE
Year	UV-A	1968–2024	0.79	3.10%
	UVery	1999–2024	0.76	3.10%
Warm period (May–September)	UV-A	1968–2024	0.83	3.20%
	UVery	1999–2024	0.83	3.10%
January	UV-A	1968–2024	0.73	11.00%
	UVery	1999–2024	0.50	17.90%
April	UV-A	1968–2024	0.83	5.60%
	UVery	1999–2024	0.85	5.40%
July	UV-A	1968–2024	0.86	4.80%
	UVery	1999–2024	0.90	4.40%
October	UV-A	1968–2024	0.88	7.90%
	UVery	1999–2024	0.82	8.70%

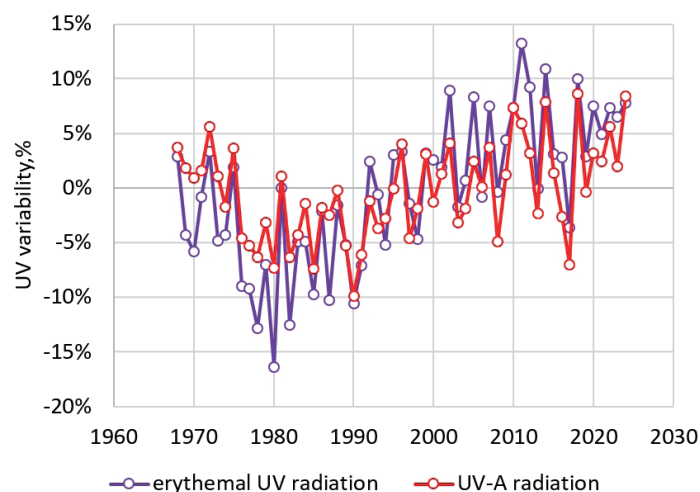


Fig. 1. Variability of annual UV-A and erythemal UV radiation in Moscow according to the reconstruction model (version 2) for the 1968–2024 period. The data are normalized over the 1968–2024 period

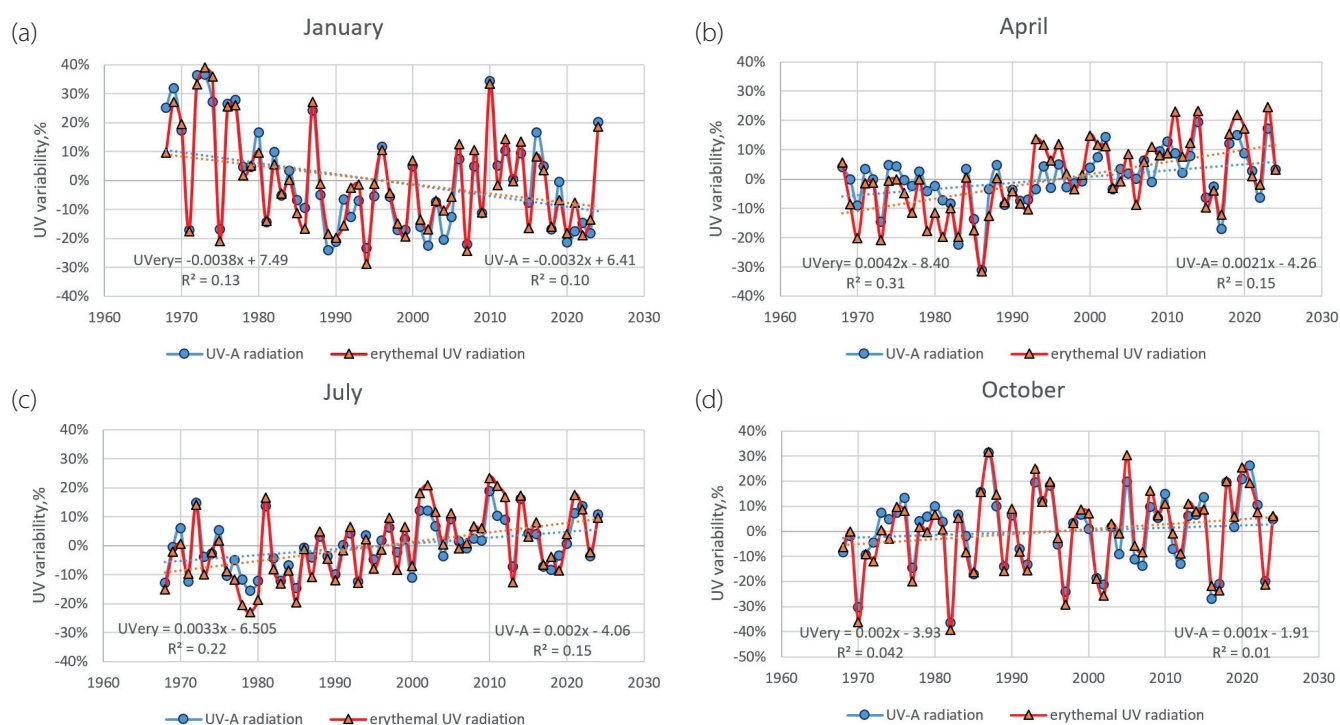


Fig. 2. Interannual variability of UV-A and erythemal UV radiation according to the reconstruction model for January (a), April (b), July (c), and October (d). The dotted lines show the linear trends for these periods

between them for erythemal and UV-A radiation are 0.97 and 0.9, respectively. The close relationship between the annual values and values during the warm season is determined by a high fraction of UV radiation during the warm season, reaching 70% for UV-A radiation and 78% for UVery due to higher solar angles in the warm period. Therefore, the higher errors of the reconstruction model during the winter season do not significantly affect the estimates of variability of annual values.

DISCUSSION AND CONCLUSIONS

An improved version of the solar radiation reconstruction model (version 2) has been proposed. This model has been configured to assess the variability of surface ultraviolet radiation in different spectral ranges. All model blocks have been modified, and a new block has been added. The application of the dependence between the radiation amplification factor due to ozone and solar angle has provided a much more accurate description of the winter UVery variations compared to those in the old version of the model. The account of the NO₂ impact on

the UV variability was added. The changes in NO₂ content provide UV response of a maximum of 0.5–0.8% in winter months. The aerosol block of the model was also modified: instead of an empirical equation, a model parameterization taking into account the optical aerosol properties has been used. This has slightly adjusted the trend of UV radiation due to aerosol. The coefficients of multiple reflection for UVery and UV-A radiation have been refined. In clear sky conditions, their values were shown to be determined by ozone for erythemal UV radiation and by aerosol for UV-A radiation. The estimates of UV variability due to cloudiness also have been refined.

Testing the model against measurement data from the Meteorological Observatory of Moscow State University has shown satisfactory results. The mean RMSE values are around 3% for annual values, which is comparable to the measurement errors themselves, especially during the first years of the UV monitoring period. The correlation coefficients between the model and measured values of UV variability are high (around 0.8), especially during the warm season, when the model uncertainties associated with surface albedo are lower. At the same time, the variability

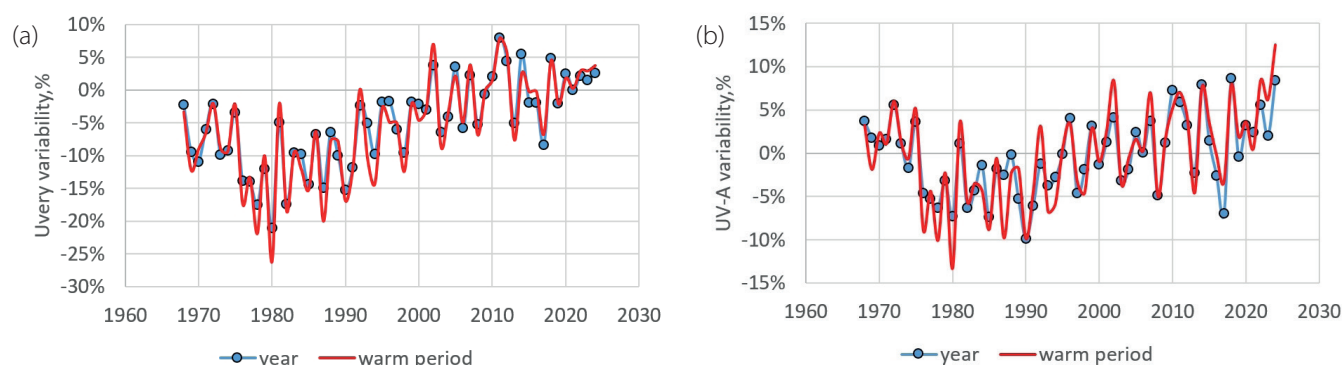


Fig. 3. Variability of UVery (A) and UV-A (B) radiation over the year and over the warm (May–September) period according to the reconstruction model in Moscow for the 1968–2024 period

of UV radiation during the warm season largely determines its annual variability, as evidenced by the corresponding high correlation coefficients between these series. The values in brackets should be changed to (around 0.9–0.97)

The previous version of the UV reconstruction model provides a similar order of the correlation coefficients for different seasons, except winter ($R = 0.4$ in the previous model vs. $R = 0.55$ in the new one). The new model has a better agreement due to a better account of cloud optical thickness and the R_x dependence on solar angle. However, the limit for further model improvement is set by the quality of the measured data with the uncertainty of approximately 5%, particularly during the cold season when air temperatures are negative.

The analysis of surface UV radiation variability over this period has revealed noticeable changes with a minimum in the late 1970s and early 1980s and a maximum after 2010. Moreover, the variations are more pronounced

for erythemal UV radiation mainly due to an additional consideration of ozone variability. At the same time, there are multidirectional UV changes in different months of the year: in January, the trend is negative, while in April, July, and October, it is positive. The positive trends in April and July are higher for erythemal UV radiation (3–4% per 10 years) compared to UV-A radiation (2% per 10 years).

Thus, the new version of the reconstruction model has enabled identification of the general features of long-term UV variability for two spectral regions and their differences. For the Moscow region the spectral differences are mainly expressed in a significantly lower UV-A changes with maximum amplitude of 19%, compared to the 30% amplitude of erythemal UV radiation.

The proposed reconstruction model can also be used for assessing the variability of solar radiation in other spectral regions after tuning several coefficients. ■

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METHODOLOGY FOR ASSESSING MICROPLASTIC QUANTITY IN CONTEMPORARY URBAN SURFACE DEPOSITED SEDIMENTS

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ABSTRACT. The aim of this exploratory study is to develop an approach for assessing the microplastic content in an urban area. Urban surface-deposited sediments (USDS) are used as a geindicator component. Three research design schemes have been proposed for determining the microplastic content in USDS. The first scheme involves manually counting polymer particles identified by Raman spectroscopy. The second scheme is based on FTIR (Fourier-transform infrared) analysis of the floating fraction of the USDS, obtained by treating the sediments with a saturated NaCl solution (120 g/L), with quantitative assessment carried out using standard samples prepared from the identified polymers and the mineral matrix. According to the third scheme, polymers in both the floating fraction and the mineral matrix of the USDS were identified using FTIR. The carbon (C), hydrogen (H), and nitrogen (N) contents were then measured. The content of the identified polymers was assessed on the basis of the C:H ratio in the USDS. The first scheme does not allow reliable identification of polymers. The second scheme did not permit reliable quantitative assessment of polymer content in the USDS. However, a combination of FTIR spectroscopy and elemental analysis of floating fraction subsamples <100 µm, separated using a 120 g/L NaCl solution, enabled the quantity of polyethylene (PE) in the USDS to be determined. The total amount of PE in particle size fraction <100 µm of the USDS a residential urban area, using Ekaterinburg (Russia) as a case study, was estimated to range between 242 and 623 tonnes, average value 352 tonnes (corresponding approximately 1100 mg/kg). The quantity of polymers contained within both the mineral matrix and the floating fraction > 100 µm of contemporary sediments remains unknown; it is evident that the total is higher. This estimate is preliminary and may be refined in future studies.

KEYWORDS: urban environment, urban surface deposited sediments (USDS), road dust, microplastic, polyethylene (PE), pollution assessment

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INTRODUCTION

The term ‘microplastic’ refers to polymer particles measuring less than 5 mm in size. A range of sources contribute to the release of microplastics into the environment, including household products, cosmetics, clothing and industrial activities (Alak et al., 2022; Xu et al., 2020). Microplastics are classified as either primary or secondary (Luo et al., 2020). Primary microplastics are manufactured to specific properties defined by the producer. Secondary microplastics, by contrast, are aged polymers and fragments resulting from the degradation of plastic items (Waldschläger et al., 2020).

Microplastics are continuously redistributed throughout the environment and have spread across all the geospheres. Plastic waste in soils is a major source of microplastic pollution in the atmosphere, water bodies and living organisms (He et al., 2018). Microplastics enter the atmosphere through water evaporation processes and the mechanical abrasion of plastic items (Wright et al., 2020). Their atmospheric transport can occur over long distances. It is estimated that 75–200 million tonnes of plastic are currently present in the world’s oceans (From Pollution to Solution, 2021). Approximately 80% of this plastic has entered the oceans via rivers and other waterways

from land-based sources (Water Pollution by Plastics and Microplastics, 2020).

The potential hazard posed by microplastic particles lies in their ability to enter the human body via the respiratory system, the gastrointestinal tract and the skin. Micron- and submicron-sized particles are capable of penetrating cell membranes and entering the bloodstream. Microplastics contain toxic compounds and additives (Acosta-Coley et al., 2019; Shen et al., 2025). Once plastic particles enter the body, these toxic substances may cause damage to internal systems. Although many additives are certified as safe, they may still migrate from polymers (Waldschläger et al., 2020; He et al., 2018; From Pollution to Solution, 2021; Water Pollution by Plastics and Microplastics, 2020).

Plankton, which forms the first link in most food chains, feeds on microplastics. Animals, birds and fish may mistake plastic particles for food. The harm caused by microplastics to humans has not yet been sufficiently studied or conclusively demonstrated (Abbasi and Turner, 2021).

Plastic itself is chemically inert and does not readily undergo chemical reactions within the body. It is generally excreted; however, nano- and microparticles may accumulate in bodily systems (Yu et al., 2024; Lim et al., 2021). The inhalation of plastic nanoparticles may lead to their accumulation in the alveoli, thereby increasing the risk of respiratory diseases (Jenner et al., 2022). The presence of polymer particles in the bloodstream has been identified as a potential contributing factor in vascular blockage and the development of atherosclerosis (Facciola et al., 2021). Health issues potentially associated with microplastic exposure include eye irritation, breathing difficulties, gastrointestinal disorders, impairment of the excretory system (including kidney and liver damage), cancers of the lung, liver and stomach, and infertility (Yu et al., 2024; Hirt and Body-Malapel, 2020; Huo et al., 2015).

There is currently a lack of a comprehensive legislative framework to regulate microplastic pollution. No established standards exist for permissible microplastic content in environmental media. Discussions are ongoing among environmental experts, scientists, environmental activists, policymakers, polymer manufacturers and other stakeholders regarding how best to address the growing presence of polymers in the environment (Global Plastics Outlook, 2022; Shingler, 2024). Polymer manufacturers advocate the proper management and disposal of plastic waste without substantially reducing polymer production. By contrast, environmental groups call for reductions in both polymer production and fossil fuel extraction (UNEP/PP/INC.3/4).

Qualitative and semi-quantitative methods are employed to determine the presence of microplastics (Alak et al., 2022; Chen et al., 2020). Raman spectroscopy requires access to comprehensive polymer spectral databases (Araujo et al., 2018; Mattsson et al., 2022). FTIR spectroscopy necessitates preliminary processing of the materials under investigation in order to avoid spectral artefacts (Andoh et al., 2024). Gas chromatography–mass spectrometry (GC–MS) is highly effective for identifying PE, PP, PS and PA particles measuring less than 1 mm (Alak et al., 2022; Fischer and Scholz-Böttcher, 2017). Visual identification enables the determination of microplastics on the basis of their morphological characteristics (Alak et al., 2022; Kotar, 2022; Zhang et al., 2018).

The collection of scientific results and data concerning the presence of polymers in the environment, their potential hazards, and their pathways of migration and accumulation is ongoing. The concentration of microplastics in an environmental compartment is

commonly expressed as the number of particles per unit volume or mass of a sample, or per unit area (Defontaine et al., 2020; Xiong et al., 2019; De Carvalho and Neto, 2016; Kitahara and Nakata, 2020). Reported values vary considerably between different regions of the world. For example, the mean concentration of polymer particles in the Adour River estuary (France) was found to be 1.13 particles/m³ (Defontaine et al., 2020). The average abundance of 0.3–5 mm particles in the Yangtze River (China) is 4.92×10^5 items/km² (Xiong et al., 2019). In the Ebro River delta (Spain), the mean abundance of polymers measuring 0.05–3 mm in water is 3.5 ± 1.4 particles/m³ (Simon-Sánchez et al., 31). Concentrations of microplastics on the beaches of Guanabara Bay (Rio de Janeiro) ranged from 12 to 1300 particles/m² in summer and from 3 to 743 particles/m² in winter (De Carvalho and Neto, 2016). The atmospheric deposition rate of microplastics in London was estimated to range from 510 to 925 particles/m²/day (Wright et al., 2020), exceeding the values reported for Paris (an average of 110 particles/m²/day) and for locations in China (20 particles/m²/day) (Wright et al., 2020). However, this mode of reporting is of limited practical value, as it does not assess the actual concentration of individual polymer types (Soininen and Koistinen, 2025). Furthermore, it does not take into account the degradation and fragmentation of plastics into progressively smaller particles.

At present, there is relatively little information on the microplastic content of environmental media in Russia, where 75% of the population lives in urban areas and is in constant contact with polymer-based materials. It is therefore essential to develop reliable methods for assessing the quantity of polymers in the environment in order to inform future regulatory measures.

One of the geoinicator components used to assess environmental conditions in urban areas is contemporary urban surface-deposited sediment (USDS), represented by road dust (RD) and sediments accumulating in local microrelief depressions (Berger, 1997; Bezberdaya et al., 2024; Seleznev et al., 2023). USDS integrates surface migration flows of pollutants within the urban environment (Seleznev et al., 2023; Seleznev et al., 2020). Data on the polymer content of USDS would substantially enhance understanding of their impact on human health in urban settings and could provide a basis for environmental impact assessments of urban areas.

This study aims to develop a method for the qualitative and quantitative assessment of microplastic content in USDS. The specific objectives were as follows:

- (1) To carry out a qualitative analysis of polymers in USDS and characterise their composition.
- (2) To perform a quantitative analysis of polymers in USDS samples.
- (3) To estimate the total amount of polymer material in USDS within a residential urban area.

The study was conducted in Ekaterinburg (Russia).

MATERIALS AND METHODS

Object of the Study

The material of two types of USDS was analysed: road dust (RD) and sediments accumulated in local surface microrelief depressions (Bezberdaya et al., 2024; Seleznev et al., 2023; Seleznev et al., 2020). The first type is represented by dust accumulating along the roadside kerb. RD is formed as a result of road surface abrasion by tyres, the transport of particles of various origins by stormwater surface run-off, and dust carried in on vehicle wheels (Bezberdaya et al., 2024). Sediments from local surface microrelief depressions

are located in courtyard areas within residential districts characterised by multi-storey buildings (Seleznev et al., 2023; Seleznev et al., 2020). They are composed of soil erosion products, particles of construction materials, concrete, asphalt and anthropogenic debris. Figure 1 presents photographs of the studied sites, together with brief descriptions of USDS.

Sample Collection, Processing and Analysis

USDS samples were collected at six sites in Ekaterinburg (Fig. 1). Each sampling site represents an elementary urban residential landscape (EURL); the concept of EURLs have been described in previous studies (Yarmoshenko et al., 2020). An EURL constitutes a typical segment of a city block and comprises the courtyard area – including functional zones such as car parks, lawns, pavements, driveways and playgrounds – together with the façade zone adjoining the street road network. A residential area therefore consists of multiple EURLs.

Typical sites were randomly selected within the city in the vicinity of the Institute of Industrial Ecology, Ural Branch of the Russian Academy of Sciences (IIE UB RAS). USDS sampling was conducted in both the façade and courtyard zones of the selected sites. Road dust was collected outside the residential blocks at three sites, while sediments were sampled from courtyard areas at the remaining three sites. At each site, a composite

sample was obtained by combining sedimentary material collected from three to five points within a façade or courtyard zone (Seleznev et al., 2023; Seleznev et al., 2020).

Samples were collected in glass beakers using a stainless steel scoop. Contact between the sample material and polymer-based materials was avoided during both collection and preparation. The mass of each sample ranged from 1.0 to 1.5 kg. Two parallel samples were collected at Site No. 6.

Sampling was carried out in Ekaterinburg on 31 July 2023 in dry weather; the sampling date was selected following a five-day dry period (according to data from rp5.ru).

The collected material was air-dried at room temperature for two weeks. During sampling and preparation, air temperatures ranged from 7.7 to 31.2°C, with a mean of 17.8°C (rp5.ru). Ambient temperature was used as the reference drying condition.

After drying, the samples were prepared for analysis. Each dry sample was sieved through a 3 mm stainless steel mesh. A ceramic pestle was used to disaggregate aggregates during sieving. The <3 mm fraction was retained for further analysis, while the >3 mm fraction was discarded. The <3 mm fraction was then quartered. Ten representative subsamples of 50 g each were obtained from every sample using the parallel quartering method. In addition, three extra parallel representative subsamples were taken from Sample No. 6.



Fig. 1. Photographs of the USDS sampling sites in Ekaterinburg:

- (A) road dust on the asphalt kerb at the courtyard exit (20 S. Kovalevskaya Street, Sample No. 1);
- (B) sediment in a storm drain at the driveway exit from the courtyard (16 S. Kovalevskaya Street, Sample No. 2);
- (C) road dust on asphalt in a car park outside a residential block (34 Komsomolskaya Street, Sample No. 3);
- (D) loose surface sediment on asphalt in a courtyard driveway (31 Komsomolskaya Street, Sample No. 4);
- (E) loose surface sediment on asphalt in a courtyard driveway (19 Komsomolskaya Street, Sample No. 5);
- (F) loose surface sediment on asphalt in a car park within a courtyard (23b Akademicheskaya Street, Sample No. 6)

In total, seven USDS samples were obtained (including the duplicate Sample No. 6). 63 subsamples of the <3 mm granulometric fraction were prepared, each weighing 50 g. The selected subsamples were analysed according to three different research design schemes.

Research Design Scheme 1

Six subsamples were randomly selected from a total set of 63 subsamples, with each subsample representing a single sampling site. To separate the fine fraction containing microplastics from the mineral matrix, a density flotation procedure was applied to each subsample. The flotation process employed a saturated NaCl solution with a concentration of 120 g/L (Thakur et al., 2023). Each entire subsample was immersed in the saturated NaCl solution, thoroughly mixed, and left to settle for two hours. The floating material was then collected, dried at room temperature, and subsequently weighed.

All particles exhibiting morphological characteristics typical of polymers (size, colour, shape, lustre, and fracture) were manually extracted from the fine fraction (Alak et al., 2022; Xu et al., 2020; Karlsson et al., 2020). This procedure was conducted using an optical microscope (XJP-H100 4-10×, Wuzhou New Found Instrument, China). Each selected particle was subsequently described and photographed. The particles were classified according to their morphological characteristics (Karlsson et al., 2020). Randomly selected particles of each type were analysed using Raman spectroscopy with a LabRam HR 800 Evolution spectrometer (Horiba Scientific, USA) at the Centre for Common Use "Geoanalytic" of the Zavaritsky Institute of Geology and Geochemistry, Ural Branch of the Russian Academy of Sciences.

Research Design Scheme 2

Six new subsamples were randomly selected from the remaining 54 subsamples, with each subsample corresponding to a single sampling site. Each subsample was treated with a saturated NaCl solution at a concentration of 120 g/L (as described in Scheme 1). The floating fraction was subsequently collected, rinsed with distilled water to remove residual NaCl, dried at room temperature, and weighed. The dried floating material was then sieved using a 100 µm stainless steel mesh.

The fraction <100 µm was analysed using a FTIR Spectrum One spectrometer (PerkinElmer, USA) equipped with diffuse reflectance and attenuated total reflectance (ATR) detectors. Normalised IR spectra were obtained over the range 500–4000 cm⁻¹ with a resolution of 0.5 cm⁻¹. Polymers were identified based on their characteristic absorption peaks (Tarasevich, 2012). The FTIR analysis was performed at the I. Ya. Postovsky Institute of Organic Synthesis, Ural Branch of the Russian Academy of Sciences. The mineral matrix and the floating fraction >100 µm were not analysed in this study.

To determine the quantity of polymer detected in the floating fraction by FTIR spectroscopy, standard samples were prepared using the polymer and mineral matrix materials. Nine standard samples containing 0.2%, 0.6%, 1%, 1.5%, 2%, 2.5%, 3%, 4%, and 5% polymer were produced and analysed by FTIR spectroscopy. A comparative analysis of the IR spectra was conducted for the floating fraction <100 µm, the mineral matrix of the subsamples, and the standard samples. A calibration curve was constructed based on the relationship between the SiO₂ content and the polymer content in the standard samples. This

calibration curve was subsequently used to determine the polymer content in the floating fraction <100 µm of the USDS.

Research Design Scheme 3

Scheme 3 analysis was conducted using three parallel representative subsamples taken from Sample No. 6. Each subsample was treated with one of the following solutions: distilled water, a saturated NaCl solution with a concentration of 120 g/L, and a saturated NaCl solution with a concentration of 240 g/L NaCl (Thakur et al., 2023).

Each entire subsample was immersed in the respective solution, thoroughly mixed, and left to stand for two hours. The floating fraction and the mineral matrix were then collected. The fine fraction and the mineral matrix treated with NaCl were subsequently rinsed with distilled water. Both the floating fraction and the mineral matrix were dried at room temperature.

After drying, the floating fraction and the mineral matrix were weighed and sieved using a 100 µm stainless steel mesh. The NaCl solutions were prepared in glass beakers and stirred with a glass rod. The floating fraction and the mineral matrix were dried in clean Petri dishes covered with glass lids. The subsamples, floating fraction, and mineral matrix were stored in paper envelopes.

The size fraction <100 µm of both the floating material and the mineral matrix was analysed using FTIR spectroscopy. Polymers were identified on the basis of their characteristic absorption peaks. The intensities of the absorption peaks corresponding to the polymers within the matrix were determined from the IR spectra. The ratio of the absorption band intensities between the polymer and the matrix was subsequently calculated. The fraction >100 µm of the mineral matrix and floating material was not analysed.

The contents of C, H, and N in the <100 µm fractions of the floating material and the mineral matrix were measured using an automatic CHN analyser PE 2400 (PerkinElmer, USA) in the Elemental Analysis Department of the I. Ya. Postovsky Institute of Organic Synthesis, Ural Branch of the Russian Academy of Sciences. The content of the identified polymer was calculated from the carbon and hydrogen contents, assuming a C:H ratio of 6:1. Based on the results of the elemental analysis, a calibration curve was constructed to describe the relationship between the intensities of the absorption peaks within the characteristic wavenumber range of the polymer and its mass content.

RESULTS

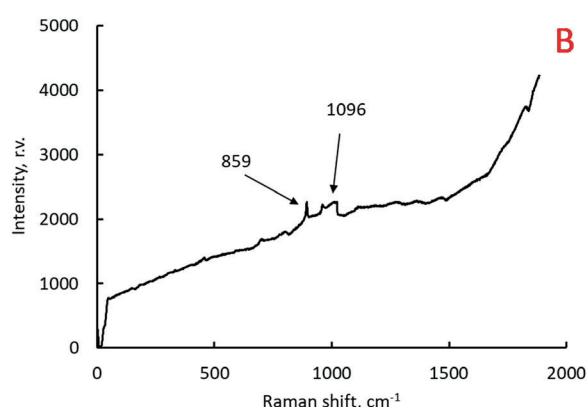
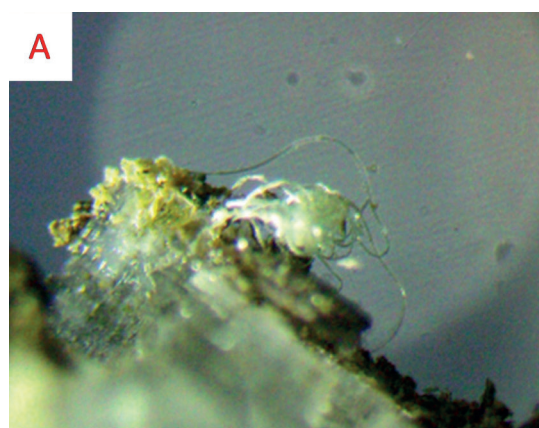
Research Design Scheme 1

A total of 240 particles were selected from six subsamples. A catalogue containing photographs of the particles was compiled. The morphological characteristics of all collected particles were described. Table 1 presents the classification of the particles by type.

Ten representative particles were analysed using Raman spectroscopy. Nine of the ten particles exhibited a peak within a specific energy range (Jin et al., 39). The spectra were compared with reference data from the Horiba Raman Spectra Database included in the technical documentation of the spectrometer. Only one of these spectra was identified as polyethylene terephthalate (PET). Figure 2 presents a photograph of this particle together with its Raman spectrum. The remaining particles could not be reliably assigned to any specific polymer on the basis of their Raman spectral peaks.

Table 1. Typical morphological characteristics of particles identified in the USDS and classified as polymers.

Type of particle	Number of particles	Morphological characteristics		
		Size, μm	Colour (number of particles)	Shape
Fiber	115	54–5000	Colourless (82), black (9), white (22), yellow (1), red (1)	Thin, stretched, curved, straight, twisted
Sphere	46	10–122	Black (43), white (2), colorless (1)	Round
Fragment	21	9–543	White (5), black (8), white (3), red (4), brown (1)	With sharp, ragged edges
Pellet	23	20–96	White (15), yellow (2), black (6)	With rounded edges
Foam	4	14–83	White (4)	Round shape with foamed structure
Film	26	47–152	Colourless (12), white (8), red (4), green (2)	Thin with ragged edges

**Fig. 2. Image of the PET fibre particle (A) and its Raman spectrum (B), peaks at wave numbers 859 and 1096 cm^{-1} (Karlsson et al. 2020; Tarasevich, 2012)**

Research Design Scheme 2

The analysis of the floating fraction $< 100 \mu\text{m}$ from six subsamples resulted in FTIR spectra with peaks in the wave number ranges of $2800\text{--}2900 \text{ cm}^{-1}$ and at approximately 1400 cm^{-1} , corresponding to C-H bonds (Tarasevich, 2012). The spectra are presented in Figure 3.

The analysis of the spectra indicates the presence of an organic component in the subsamples. The absorption peaks observed in the wave number range $3500\text{--}3100 \text{ cm}^{-1}$ correspond to N-H bonds (Tarasevich, 2012). Peaks at approximately 3600 cm^{-1} are attributed to O-H bonds (Tarasevich, 2012). The subsamples are therefore presumed to contain polyethylene (PE) or polypropylene (PP) particles. The most prominent absorption peak, at a wave number of 980 cm^{-1} , corresponds to Si-O bonds and represents the mineral matrix of the USDS (Seleznev et al., 2019). Comparison of the obtained spectra with published reference spectra for PE and PP resulted in the identification of PE in the USDS (Gulmine et al., 2002).

The standard samples were prepared from the SiO_2 fraction $< 100 \mu\text{m}$ and PE granules $< 1 \text{ mm}$ in size. The standard samples contained 0.2%, 0.6%, 1%, 1.5%, 2%, 2.5%, 3%, 4%, and 5% PE. Figure 4 presents the FTIR spectra of the standard samples.

The absorption peak for the standard sample containing 2% PE (in the wave number ranges of $2800\text{--}2900 \text{ cm}^{-1}$ and at 1400 cm^{-1}) was observed at low intensity (Fig. 4, E). The peak at a wave number of 980 cm^{-1} corresponds to SiO_2 in the mineral matrix of the standard samples. No detectable PE content was identified in the remaining standard samples. Consequently, a calibration curve relating SiO_2 and PE content in the standard samples could not be

constructed. It was therefore not possible to estimate the polymer content in the floating fraction $< 100 \mu\text{m}$ of the subsamples.

Research Design Scheme 3

Figure 5 presents the FTIR spectra of the $< 100 \mu\text{m}$ fraction of the floating material and the mineral matrix of Sample No. 6 after separation using different solutions. The spectra of the floating fraction and the matrix separated with distilled water, as well as with a NaCl solution at a concentration of 240 g/L , do not differ in the intensity of the peaks at $2800\text{--}2900$ and 1400 cm^{-1} . In contrast, a significant difference in the intensity of the peaks at $2800\text{--}2900$ and 1400 cm^{-1} is observed between the spectra of the floating material and the matrix separated using a NaCl solution with a concentration of 120 g/L .

Table 2 presents the results of the elemental analysis of the $< 100 \mu\text{m}$ fraction of the floating material and the mineral matrix of Sample No. 6 after separation using different solutions (distilled water and NaCl solutions at concentrations of 120 and 240 g/L). It also includes the results of the analysis of the $< 100 \mu\text{m}$ fraction of the floating material from Samples No. 1–6, separated using a 120 g/L NaCl solution (prepared in accordance with Scheme 2). The PE content in the samples ranges from 5.54% to 14.28% by mass. However, plotting a calibration curve to describe the relationship between the absorption peak intensities within the characteristic wave number range of the polymer and its mass content did not demonstrate the expected correlation between PE content and the FTIR spectroscopy results.

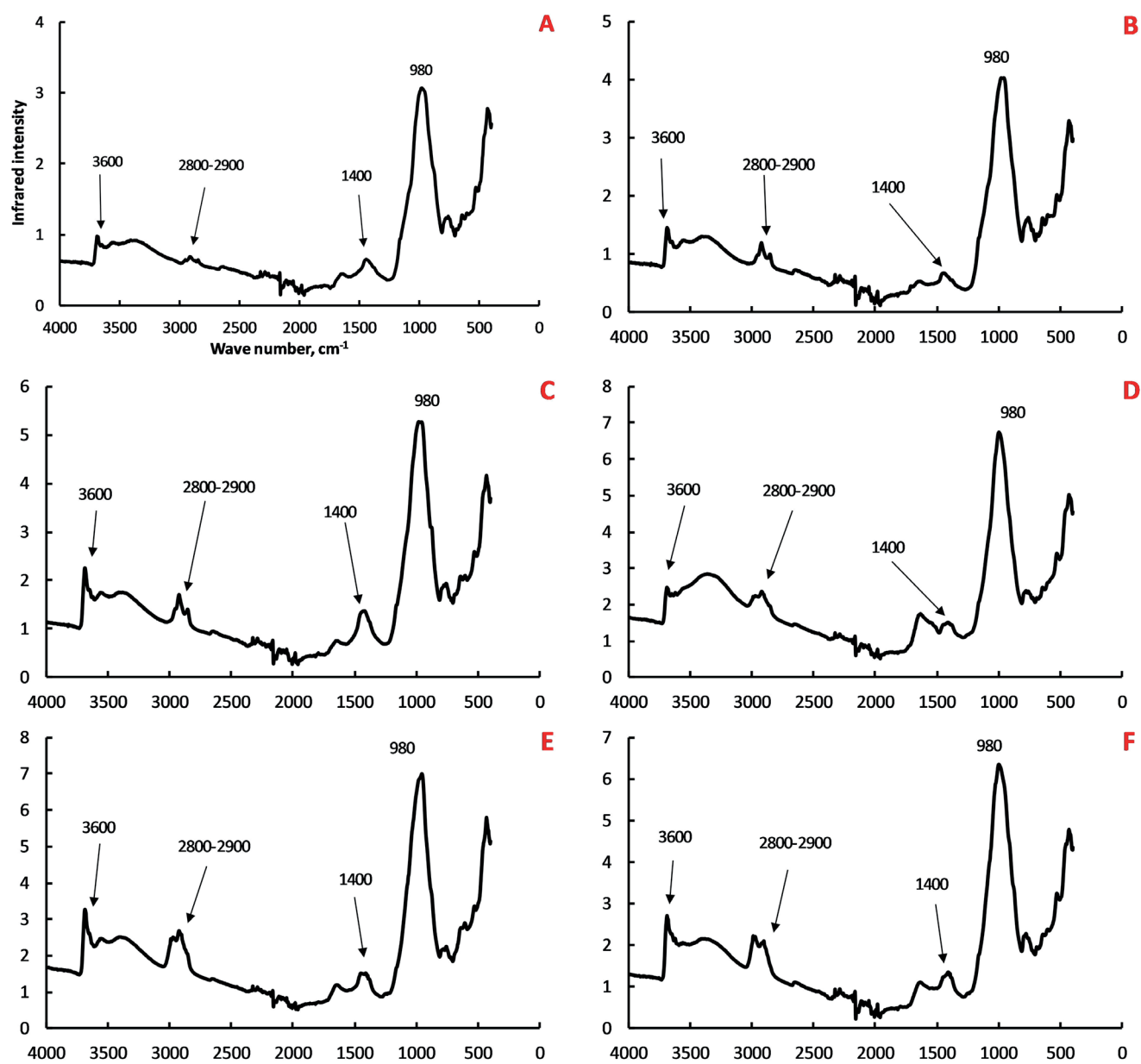


Fig. 3. FTIR spectra of the < 100 μm floating fraction from the USDS samples: A – sample No. 1, B –No. 2, C – No. 3, D – No. 4, E – No. 5, F – No. 6

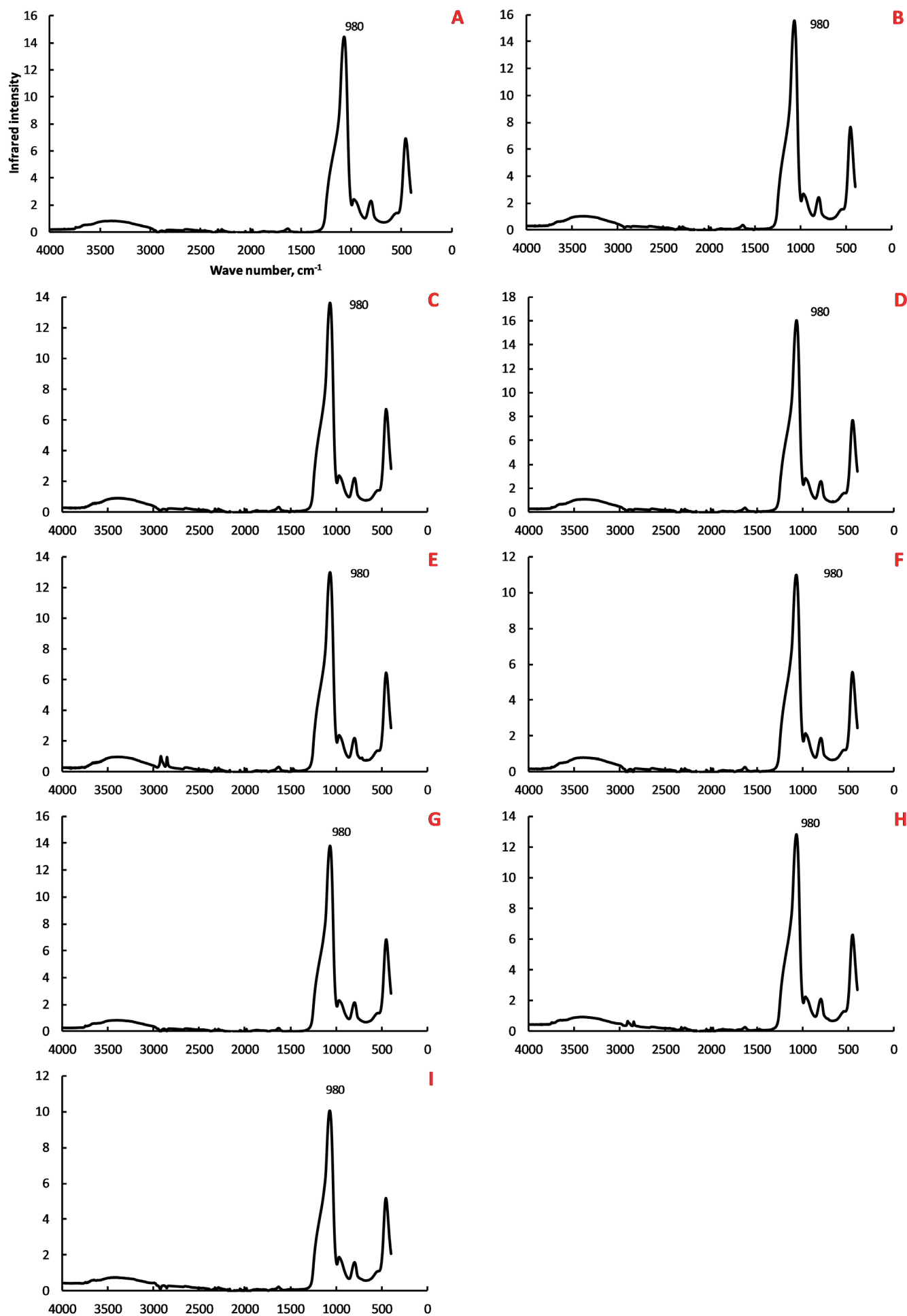


Fig. 4. FTIR spectra of the standard samples (mass % PE): A – 0.2%, B – 0.6%, C – 1%, D – 1.5%, E – 2%, F – 2.5%, G – 3%, H – 4%, I – 5%.

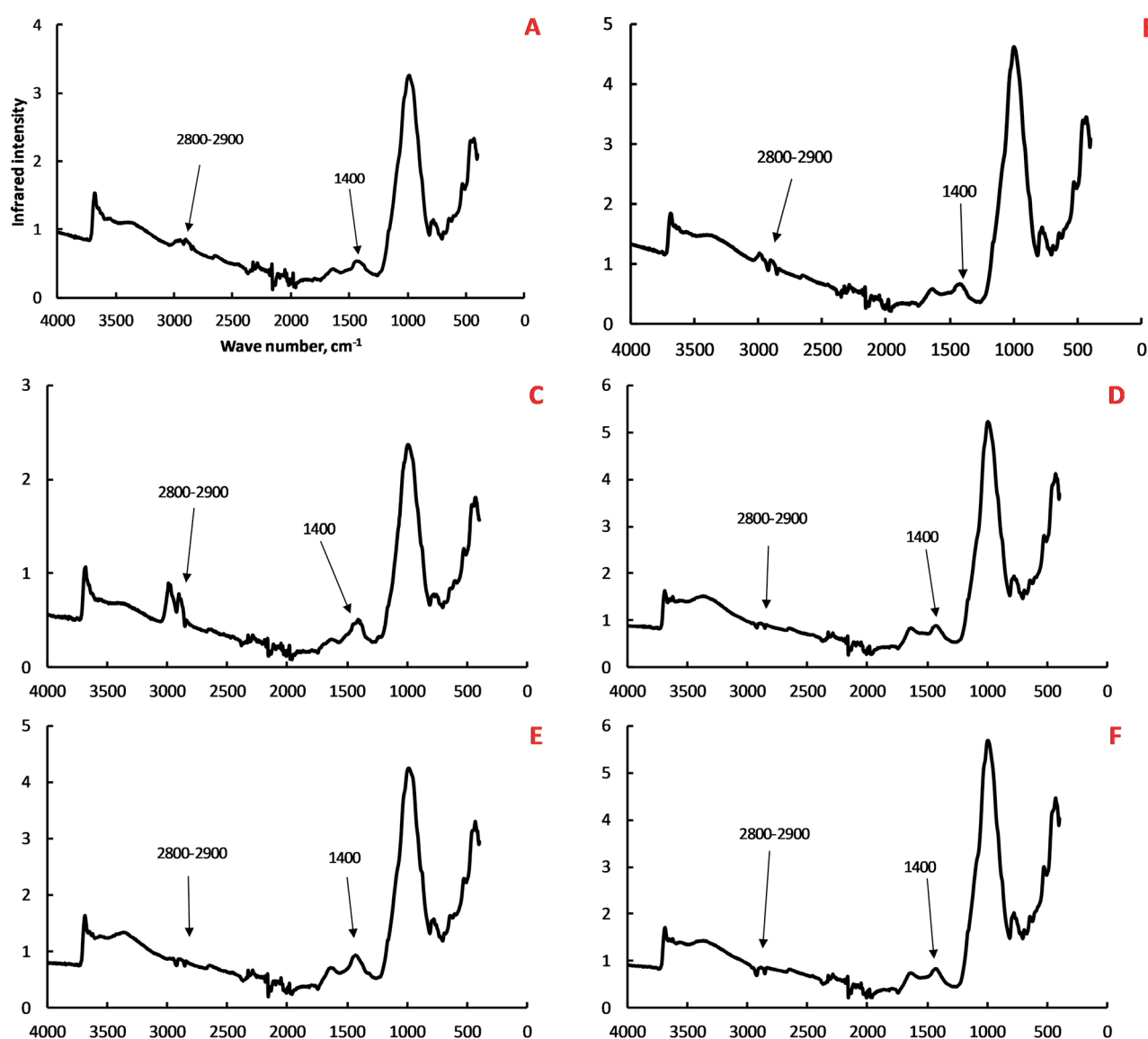


Fig. 5. FTIR spectra of the <100 μm fraction of the floating material and the mineral matrix of sample No. 6 after separation with different solutions:

A – floating fraction after separation with distilled water;

B – mineral matrix after separation with distilled water;

C – floating fraction after separation with NaCl solution at a concentration of 120 g/L;

D – mineral matrix after separation with NaCl solution at a concentration of 120 g/L;

E – floating fraction after separation with NaCl solution at a concentration of 240 g/L;

F – mineral matrix after separation with NaCl solution at a concentration of 240 g/L

Microplastic Content in the USDS

The assessment of microplastic content in the USDS within the city's residential area is based on the data obtained from Schemes 2 and 3. The average mass content of the polymer in the study area was calculated using the following equation:

$$\omega = (\sum \omega_i) / n \quad (1)$$

where ω_i is the mass content of the polymer in the i^{th} -sample, n is the number of samples.

The average PE content in the <100 μm fraction of the floating material in the USDS was $\omega = 8.07\%$ by mass within the studied residential area of Ekaterinburg, as calculated using Equation (1) and the data presented in Table 2. The minimum and maximum PE contents were 5.54% and 14.28% by mass, respectively.

The total residential area of Ekaterinburg is 128 km^2 . The total quantity of USDS amounts to 3.2×10^5 tonnes. The proportion of the particle size fraction <100 μm in the USDS within courtyard areas is 34.5% (Seleznev et al., 2019), and the proportion of floating material in the USDS is 0.0395 (based on gravimetric measurements). The mass of the floating material in the USDS is calculated as follows:

$$m_{\text{floating fraction}} = 3.2 \times 10^5 \times 0.0395 = 1.264 \times 10^4 \text{ tonnes.}$$

The mass of the < 100 μm fraction within the floating material in the USDS is calculated as follows:

$$m_{<100\text{ floating fraction}} = 1.264 \times 10^4 \times 0.345 = 4.36 \times 10^3 \text{ tonnes.}$$

Thus, the total PE content in the < 100 μm fraction of the floating material in the USDS within the city was estimated as follows:

$$\omega_{\text{min}} = 4.36 \times 10^3 \times 0.0554 = 242 \text{ tonnes,}$$

$$\omega_{\text{max}} = 4.36 \times 10^3 \times 0.1428 = 623 \text{ tonnes,}$$

$$\omega_{\text{average}} = 4.36 \times 10^3 \times 0.0807 = 352 \text{ tonnes,}$$

where the minimum, average and maximum PE contents by mass are 0.0554, 0.0807 and 0.1428, respectively (according to the data from the Table 2).

Table 2. The concentration of C, H and dry residue in the < 100 µm fraction of the floating material and in the < 100 µm fraction of the mineral matrix of Sample No. 6 after separation using different solutions (distilled water and saturated NaCl solutions at concentrations of 120 g/L and 240 g/L), as well as the < 100 µm fraction of the floating material from Samples No. 1-6, separated using a 120 g/L NaCl solution (analysed in accordance with Scheme 2), the ratio between the intensities of the PE and matrix peaks and the PE content in the subsample

Sample No. / FM or matrix / Research Design Scheme	Solution	Concentration, % by mass			PE content, % by mass	The ratio between the intensity of the PE and matrix peaks	
		C	H (N)	Dry residue		2921/980	1400/980
6 / FM / 3	distilled water	5.13	1.07	93.8	5.98	0.06	0.05
6 / matrix / 3		4.20	0.89	94.91	4.89	0.04	0.05
6 / FM / 3	NaCl, 120 g/l	4.39	0.72	94.89	5.11	0.21	0.21
6 / matrix / 3		4.15	0.90	94.95	4.83	0	0.05
6 / FM / 3	NaCl, 240 g/l	6.93	1.21	91.86	8.07	0.03	0.05
6 / matrix / 3		4.24	0.86	94.9	4.94	0	0.06
1/ FM / 2	NaCl, 120 g/l	5.47	0.77	84.16	6.37	0.044	0.087
2/ FM / 2		4.76	0.69	90.66	5.54	0.15	0.065
3/ FM / 2		6.12	1.01	87.82	7.13	0.15	0.14
4/ FM / 2		12.25	1.70 (0.56)	74.03	14.28	0.15	0.046
5/ FM / 2		7.95	1.40 (0.36)	83.03	9.26	0.2	0.081
6/ FM / 2		5.02	0.89	86.42	5.85	0.18	0.089

FM – floating material

DISCUSSION

The current exploratory study has enabled us to define the direction for developing a methodology for the qualitative and quantitative assessment of the total microplastic content in urban environments. Contemporary sediments and their various types are a relatively new geo-indicator of the urban environment. The methodology for studying them is still under development. This study combines and adapts existing field and laboratory methods used for other urban environmental compartments into three research design schemes. This takes into account the limitations imposed on the application of these methods in an urban environment. The three research design schemes shared a common procedure for collecting and preparing samples. At each stage of the research, there is a risk of sample contamination or of failing to obtain sufficient results. Nevertheless, estimates of the quantity of polymers in USDS have been obtained in this study. A discussion of the research design and approaches, including their shortcomings and potential biases, is provided below.

Residential area where the USDS samples were collected are characterised as typical for urban environment, based on the results and methodology established in previous studies (Yarmoshenko et al., 2020). The sampling sites and the samples collected in this residential area can therefore be considered representative of the city's residential environment (Seleznev et al. 2023; Seleznev et al. 2020; Seleznev et al. 2019; Bezberdaya et al., 2024). In this study, we do not consider the input of polymers into the environment during the winter period; however, we take into account that USDS in the city's residential areas may

contain material remaining after the melting of snow and snow-dirt sludge (Seleznev et al., 2019).

Micron- and submicron-sized polymer particles may have been lost during sample processing. As the samples were prepared in a standard laboratory, they may have become contaminated with submicron polymers from the air, the operator's clothing, and other sources. During the quartering process, some of the polymer material may have remained in the tailings and therefore not been included in the subsample for analysis. The samples were dried at room temperature to prevent changes in the polymer structure or other factors that could affect the assessment of polymer quantity, such as degradation or melting. However, selecting parallel subsamples from the samples for analysis ensures that the resulting estimates of polymer quantity are reasonably representative.

Research Design Scheme 1

The number of particles analysed using the visual diagnostic method is quite large. When carrying out this research scheme, it is possible that some of the polymer particles remained within the mineral matrix and were therefore not included in the analysis. Moreover, polymer particles may have acted as centres on which salt crystallised during the sample preparation process. In such cases, the operator may not be able to recognise all polymer particles. To ensure reliable identification, all polymers must exhibit several peaks in the Raman spectrum (Jin et al., 2022).

The absence of peaks in the particle Raman spectrum may be caused by:

- interference associated with elements whose energy

is close to that of the object under study;

- inaccurate laser targeting of the particle under study;
- poor sample preparation (the samples were not washed to remove salt);
- poor laser guidance by the operator during the measurement process.

The manual separation of particles from the subsample and their identification using an optical microscope combined with Raman spectroscopy is very labour-intensive and does not allow a large number of particles to be analysed in a short period of time. This method is therefore not suitable for determining the amount of microplastic in environmental samples, either qualitatively or quantitatively.

Research Design Scheme 2

The subsamples were also randomly selected for Scheme 2. The FTIR spectrum was obtained for the floating material and the matrix in each subsample. PE was found in the <100 µm fraction of the floating material in samples taken from the courtyard and façade areas of the quarter. PE is the most easily identifiable polymer. It is also likely to be present in the larger fractions and in the mineral matrix, which were not analysed. The subsamples probably contain other polymers, but their identification is difficult due to their low concentrations.

The peaks characteristic of SiO₂ were obtained for the standard samples and the <100 µm fraction of the floating material (Figures 3 and 4). The mineral composition of the USDS is represented by rock-forming minerals, of which quartz accounts for about 20%. The remaining 80% consists of other minerals (Seleznev et al., 2019). Scheme 2 is based on the assumption that the composition of the USDS fraction <100 µm in urban areas consists of PE and SiO₂; however, this is not correct. The mineral composition of the matrix can introduce errors when determining polymers using FTIR spectroscopy. The composition of USDS is influenced by a large number of factors in the urban environment. To analyse the polymer content in USDS, standard samples should be prepared using the polymer and a multicomponent mineral mixture. The heavy mineral fraction of the sample, which settles in a NaCl solution during separation, can be used as a matrix for preparing a standard sample after washing, calcination, and analysis of the polymer content.

Signals were expected in standard samples containing up to 5% PE by mass; however, none of the measured samples showed a PE signal. At the same time, the PE content of the standard samples was limited to 5%. It is possible that samples with a higher PE content should have been tested. The assumption of a maximum PE content of several per cent in the soil is based on literature data on the amount of PE in soil (Büks and Kaupenjohann, 2020). While it is difficult to determine the exact cause of the failure of Scheme 2, it is most likely due to the heterogeneity of the sample rather than the sensitivity of the spectrometer (PE is reliably detected in sediments; see Figure 3).

In the standard samples that had been prepared, the polymer particles and the matrix material had different sizes. The size of the PE granules is non-uniform and varies widely within the range of <1 mm. The results of FTIR spectroscopy of the floating material of the USDS and the standard samples may depend on particle size. When analysing the particle size fraction <100 µm of the USDS subsample, we know that the size of the polymer particles in it is <100 µm. However, the size and number of PE granules in the standard samples of 100 µm and 100–1000

µm remain unknown. Therefore, Scheme 2 is not suitable for the quantitative assessment of the polymer content in USDS.

The approach applied in Scheme 2 could be made quantitative by preparing standard samples in which the size and number of PE particles are comparable to those of the particles in the USDS. However, such a procedure would be very labour-intensive and possibly pointless.

Research Design Scheme 3

Water does not separate the polymer from the matrix. A saturated NaCl solution at 240 g/l is also unable to separate the polymer completely. A 120 g/l saturated NaCl solution partially separates the matrix from the polymer, but the separation is incomplete. The peak intensities for the floating material and the matrix separated with the 120 g/l solution are significantly different.

Elemental analysis enabled the determination of the PE content; however, other organic substances (such as plant residues and other polymers not identifiable by FTIR spectroscopy) may also have been present in the samples. The results of the FTIR spectroscopy previously conducted on the same samples are corroborated by the elemental analysis data. Nevertheless, no correlation was found between the PE content in the samples and the ratio of the intensity of the PE absorption peaks to those of the mineral matrix. This lack of correlation can be explained by the presence of other organic substances in the sample, which could potentially be removed through more thorough preparation of the USDS samples. The PE content observed in the USDS samples is relatively high (up to 14% of the organic matter mass). However, this concentration is found only in the fine fraction < 100 µm. As such, the PE content obtained from the USDS samples should be considered a minimum value for future assessments.

When conducting research according to Scheme 3, microplastic particles may remain within the matrix due to their dispersibility. It can be hypothesised that both the floating fraction and the matrix were contaminated with a substance (or other organic materials) that attenuated the intensity of IR radiation absorption. Moreover, the C/H ratio was reliably obtained. Additional treatment could be employed to remove this contamination and separate the microplastic from the matrix, for example, by combining flotation in a NaCl solution with ultrasound.

Microplastic Content in the USDS

The estimates of the amount of polymers obtained in this study are very rough and may represent the minimum values for polymer concentrations in urban residential areas. The estimated polymer content does not account for coarse microplastic fragments (> 3 mm). The average value of the total PE content (352 tonnes) corresponds to 1100 mg/kg. It is comparable the estimate for the fraction <1000 µm of microplastic in urban soils in Sydney (Büks and Kaupenjohann, 2020). However, this estimate is higher than the amount of microplastics in the soils of agricultural lands and non-urban areas (Yang et al., 2021; Gündoğdu et al., 2025).

The estimate was obtained for the floating fraction < 100 µm, while the quantity of polymers contained within both the mineral matrix and the floating fraction > 100 µm of contemporary sediments remains unknown; it is evident that the total is higher. At the same time, only one polymer, polyethylene, was identified, and the quantity of others remains unknown. These may also be present in contemporary sediments within urban areas.

The procedures employed in this study to separate the floating fraction through treatment with a NaCl solution are fairly common in practice; however, the methods for processing samples require further improvement. The sampling sites were selected within the city, in close proximity to the laboratory, to facilitate the delivery of samples without the use of plastic containers.

CONCLUSIONS

Visual analysis combined with Raman spectroscopy for particles visually resembling polymers does not permit the reliable identification of polymers in samples from the contemporary urban environment. This approach is also unsuitable for quantifying polymers in environmental compartments.

The use of distilled water and a saturated NaCl solution at a concentration of 240 g/L failed to separate the polymer completely from the USDS samples. This was confirmed by FTIR spectroscopy analysis of the floating fraction.

A saturated NaCl solution at a concentration of 120 g/L does separate polymers from the mineral matrix into the floating material. However, a portion of the microplastic

remains within the matrix due to its dispersibility. Polyethylene (PE) was detected in the floating fraction using FTIR spectroscopy. To quantify the PE content, standard samples were prepared from a mixture of PE and SiO₂ with varying known PE concentrations. Analysis of these standard samples by FTIR spectroscopy did not reveal the presence of PE. The results of FTIR spectroscopy for both sediment samples and standard samples are dependent on particle size. The microplastic particles in the samples are < 100 µm, which does not correspond to the size of the PE granules used in the prepared standard samples (< 1 mm). To refine the proposed method for quantitative analysis, it is necessary to create standard samples in which the size of the PE particles matches the size of the particles in the sample under investigation. The combination of FTIR spectroscopy and elemental analysis applied to the floating fraction (< 100 µm) separated using a 120 g/L NaCl solution enabled the quantification of PE in the USDS samples. The total quantity of PE in the urban residential area was estimated to be in the range of 242–623 tonnes; this figure is approximate and may be refined in future studies. ■

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CONCENTRATION OF PHTHALATES IN THE ATMOSPHERIC SURFACE LAYER IN A MONSOON CLIMATE CONDITIONS (THE CASE OF VLADIVOSTOK CITY)

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ABSTRACT. The study is aimed at assessing the concentration of phthalic acid esters (dibutyl phthalate — DBP, diisobutyl phthalate — DIBP, diethylhexyl phthalate — DEHP) in suspended particles of the atmospheric surface layer in monsoon climate conditions of Vladivostok city. The relevance of the work is due to the paucity of data on airborne phthalate pollution in the territory of the Russian Federation and the unique climatic conditions of the region influencing their distribution.

Samples were taken during the period of 2014–2022 in two zones, specifically, the urban area (Vtoraya Rechka) and the background area (Russky Island). The gas chromatography with mass spectrometry was used for the sample analysis. It has been found that the DBP and DEHP concentrations in the urban area are significantly higher than those in the background area (6.22 and 10.39 ng/m³ versus 3.34 and 8.61 ng/m³, respectively), which is associated with the presence of anthropogenic sources. Almost no differences between the investigated zones were revealed for DIBP concentration (7.17 and 6.08 ng/m³). This homogeneity likely results from a combination of widespread source distribution and the physicochemical properties governing its environmental transport. The analysis showed significant negative correlations of phthalate concentrations with key meteorological parameters (temperature, humidity, wind speed; $r = 0.60\text{--}0.84$) and a strong positive correlation with vehicle traffic intensity ($r = 0.72\text{--}0.77$), confirming the influence of anthropogenic and natural factors on the distribution of phthalates. Concentrations of phthalates in Vladivostok turned out to be lower than in Asian industrial cities but higher than in European cities. The research outcomes can be used when developing measures to reduce phthalate emissions and predicting their concentrations in a monsoon climate conditions.

KEYWORDS: phthalates, atmospheric surface layer, solid suspended particles, monsoon climate

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INTRODUCTION

Phthalates, which are esters of 1,2-benzenedicarboxylic acid, are being widely used in industry for almost a century, primarily as plasticizers. Their widespread use began back in the 1930s and continues to the present, despite growing concerns about their potential toxicity. High molecular weight phthalates, such as diethylhexyl phthalate (DEHP), are mainly used in the production of polyvinyl chloride (PVC) materials (Afshari et al., 2004; Eichler et al., 2019). These compounds are part of a wide range of products including building materials, medical products, and children's products (Hahladakis et al., 2018; Tickner et al., 2001). Their main function is to ensure the plasticity and flexibility of polymer compositions (Rahman and Brazel, 2004). At the same time, low molecular weight phthalates

are more often used in household and industrial chemicals. They are included in formulations of solvents, adhesives, cosmetics, pharmaceuticals, and insecticides (Heudorf et al., 2007).

Modern industry uses more than 60 different types of phthalates that confirms their wide functionality and chemical diversity (Monti et al., 2022). These compounds are widely used in the production of lubricants, paint and varnish products, printing inks, and many other technical and consumer goods. However, the specificity of their molecular integration with the polymer matrix is physical, rather than chemical binding. This circumstance causes a high susceptibility of these substances to migration into the environment (Songue Same et al., 2023). Under the impact of external factors, such as temperature fluctuations, ultraviolet radiation level, changes in the acid-

base balance, and mechanical action, phthalates desorb, evaporate, or leach out (Afshari et al., 2004). When released from materials, phthalates are adsorbed on solid particles and can move in the atmosphere, penetrate soil and aquatic ecosystems through landfill filtrates, wastewater, as well as agricultural and stormwater runoff (Net et al., 2015).

Several key phthalates are commonly detected in the air. These are dimethyl phthalate, diethyl phthalate, dibutyl phthalate (DBP) and its isoform diisobutyl phthalate (DIBP), benzylbutyl phthalate, diethylhexyl phthalate, and dioctyl phthalate. Due to the potential toxicity and widespread occurrence of these compounds, various restrictions have been imposed on their use in a number of countries, including the USA, the European Union, China, Japan, and India (Monti et al., 2022).

The human body is exposed to phthalates in various ways: transdermal penetration, intake through the respiratory system, as well as by ingestion with food and drinking water (Benjamin et al., 2017). The most dangerous are urbanized areas, where high concentrations of phthalates in the surface air create conditions for constant and uncontrolled exposure of these substances with the people. Children, pregnant women, and people with weakened immune systems are particularly vulnerable to the chronic impacts of these xenobiotics (Huang et al., 2016; Jurewicz and Hanke, 2011; van't Erve et al., 2019).

Toxicological studies of the recent decade have convincingly confirmed that phthalates can have complex adverse effects on various human physiological systems, and significantly – on the respiratory and immune systems (Yu and Wang, 2024; Zhang et al., 2022). It has been established that exposure to these compounds can cause inflammatory responses, promote the development of allergic diseases, and disrupt the barrier function of the respiratory epithelium (Baek et al., 2021; Bølling et al., 2020; Rafael-Vázquez et al., 2018). One of the studied molecular mechanisms is the ability of individual phthalates, such as DBP, to suppress the activity of the erythroid 2-related nuclear factor (Nrf2), a key regulator of the antioxidant protection of cells (Zeng et al., 2022). This leads to increased production of reactive oxygen species, including from neutrophil granulocytes, and, as a result, to the induction of oxidative stress.

In modern studies of the spread and transformation of phthalates, climatic and meteorological conditions are considered to be key factors determining their behavior in the atmospheric environment (Huo et al., 2023; Munyaneza et al., 2023). In particular, zonal features of temperature, humidity, and precipitation affect the rate of adsorption and desorption of phthalate compounds with suspended solids, their phase distribution between the gas and solid phases, as well as the intensity of photochemical and hydrolytic processes. The Vladivostok city is located on the coast of the Sea of Japan in a zone of strong seasonal temperature fluctuations and high relative humidity. Moreover, significant automotive traffic and heavy maritime traffic create background levels of organic plasticizer emissions, whose degree of migration and degradation can vary significantly depending on prevailing climatic and weather conditions. Monitoring in Vladivostok can allow not only obtaining unique data on seasonal changes in phthalate concentrations, but also developing adaptive models of their distribution with regard to coastal regions.

It should be emphasized that this study is of particular value due to the lack of systematic data on phthalates in atmospheric air in the Russian Federation in general, and especially in the Far Eastern region. In this regard, the main task of the present research is to assess the level of air

pollution with complex phthalic acid esters in Vladivostok city.

MATERIALS AND METHODS

The suspended particulate matter (SPM) was sampled at two sites: a background site on Russky Island and an urban site in the Vtoraya Rechka district (Fig. 1). Air samples were collected on a seasonal basis from 2014 to 2022. In total, 693 samples were obtained: 426 from the urban area (Vtoraya Rechka district) and 267 from the background site (Ekipazny settlement on Russky Island). The seasonal distribution for the urban site was 81 (autumn), 60 (winter), 94 (spring), and 191 (summer), and for the background site it was 120 (autumn), 40 (winter), 53 (spring), and 54 (summer). Given the ubiquity of phthalates, stringent measures were implemented to minimize contamination. Specifically, field blanks were collected for each air sampling session, and all filter handling was performed using phthalate-free gloves and glass laboratory equipment.

Sampling was conducted employing a PU-4E aspirator by means of a high-speed Richter absorber. A single-episode air sampling was carried out at a height of 1.5 meters above ground level. The air intake rate was 35 liters per minute, and the particles were collected using an AFA-VP-20 filter. Meteorological indicators (air temperature, humidity, pressure, wind speed and direction) as well as automotive traffic data were recorded during each cycle. Automotive traffic intensity was quantified through manual counts. For each sampling session, the number of vehicles passing the sampling site was recorded per minute at several time points, and the resulting values were averaged to obtain a mean traffic intensity value for the sampling period. Meteorological data were taken from Primorsky Department of Hydrometeorology and Environmental Monitoring (Primhydromet).

The qualitative and quantitative analysis of phthalates associated with suspended particulate matter was performed by gas chromatography method coupled with mass spectrometry (GC–MS) employing a Shimadzu GCMS-QP 2020 gas chromatograph. Chromatographic separation was performed using a SH-Rtx-5MS capillary column (30 m × 0.25 mm, phase thickness of 0.25 microns) in a linear temperature change mode. Initial temperature was 160 °C (2 min), heating rate to 260 °C was 2 °C/min, final isothermal stage was conducted for 10 min. The temperature of the injector was maintained at 250 °C. Helium at a flow rate of 0.6 ml/min was used as the carrier gas. The mass spectra were acquired at an ion source temperature of 200 °C. The chromatographic and spectral data were processed using GCMS Postrun Analysis software package. The quantitative assessment of phthalate concentrations (expressed in ng/m³) was performed using calibration curve technique based on the analysis of standard solutions of the target compounds. The dibutyl phthalate, diisobutyl phthalate, and diethylhexyl phthalate standards were acquired from Dr. Ehrenstorfer GmbH (Augsburg, Germany).

Statistical data processing was performed using the StatSoft Statistica 10.0 software package. The data were presented as a median and quartiles (25-th and 75-th percentiles). The Kruskal–Wallis test was used to assess the statistical significance of the differences between the groups. The influence of climatic factors was assessed using Spearman correlation analysis. The multiple regression equation was obtained using the Multiple Regression module in the Statistica 10.0 package. When testing statistical hypotheses, the critical significance level (p) was considered significant at $p < 0.05$.



Fig. 1. Map with sample collection points and their characteristics

RESULTS AND DISCUSSION

The data analysis for the period of 2014–2022 has shown the content of three types of phthalates in the air volume of both zones: dibutyl phthalate (DBP), diisobutyl phthalate (DIBP), and diethylhexyl phthalate (DEHP). The results obtained indicate significant differences in the content of DBP and DEHP between the urban and the background areas (Table 1). In the urban area, the median concentrations of DBP and DEHP were 6.22 and 10.39 ng/m³, respectively, which is 1.9 ($p < 0.001$) and 1.2 ($p < 0.01$) times higher than those detected in the background area (3.34 and 8.61 ng/m³, respectively). This is due to the high anthropogenic load in the area of the Vtoraya Rechka, where the main source of pollution is automotive transport (releasing both plastic components and exhaust gases).

No significant differences between the two areas were detected for DIBP (7.17 ng/m³ in the city and 6.08 ng/m³ on the island). Whereas DEHP, due to its higher molecular weight, expectedly exhibited lower mobility and a more pronounced local distribution, the observed spatial differences for DBP, contrasted with the absence of such variability for DIBP, are likely driven by a combination of differences in source types, emission patterns, and gas–particle partitioning. DBP is commonly associated with personal care products and other localized, intermittent emitters, whereas DIBP may originate from more broadly

distributed materials and numerous small, diffuse sources, resulting in a more uniform spatial distribution. Verification of this hypothesis requires dedicated measurements of its distribution across the gas and particle phases.

Correlation analysis has revealed a significant relationship between phthalate concentrations and climatic and anthropogenic factors (Fig. 2). Negative correlations with temperature ($r = -0.71$ for DBP), humidity ($r = -0.84$ for DEHP), and wind speed ($r = -0.68$ for DBP) are explained by increased desorption and particle dispersion in adverse weather conditions. For example, high temperatures in summer activates the evaporation of phthalates from polymers, but at the same time increase their degradation, reducing the final concentration in the air.

The positive correlation with automotive traffic ($r = 0.72$ – 0.77) confirms the key role of vehicles as a source of phthalate pollution. This is especially noticeable in the urban area, where heavy automotive traffic contributes to the constant flow of plasticizers from tires, interior upholstery, and exhaust systems.

The variations in phthalate concentrations were analyzed in different year seasons (Tables 3–5).

The highest concentrations of all three phthalates were detected in autumn and spring due to a combination of moderate temperatures, high humidity, and stable wind conditions that contribute to the accumulation of particles. The median DBP values in the urban area reached

Table 1. Distribution of phthalates in different districts of Vladivostok.

Phthalates	Area	Median (Q25–Q75) ng/m ³	p-level
DBP	Urban area	6,22 (5.47–7.1)	p<0.00
DBP	Background area	3,34 (2.78–4.27)	
DIBP	Urban area	7,17 (6.62–8.04)	p<0.01
DIBP	Background area	6,08 (5.31–6.94)	
DEHP	Urban area	10,39 (9.66–11.12)	
DEHP	Background area	8,61 (7.87–9.22)	

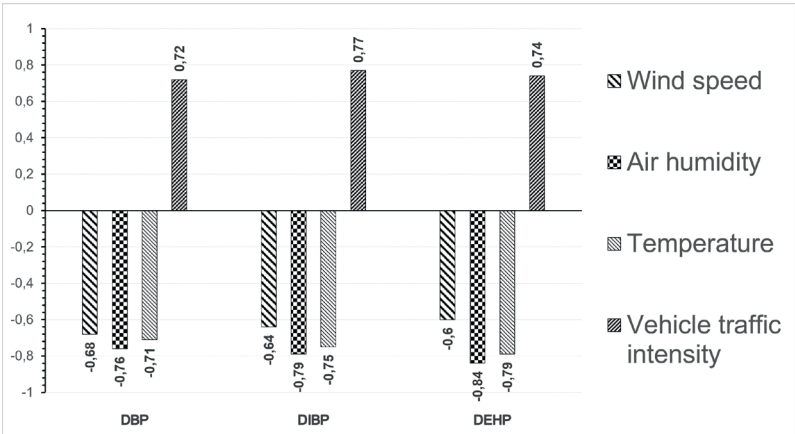


Fig. 2. Correlation coefficients of phthalate concentration with climatic and weather factors, and intensity of vehicle traffic

Table 2. Correlation coefficients of phthalate concentration with climatic and weather factors, and intensity of vehicle traffic

Year season	Area	Median (Q25–Q75) ng/m ³	p
Autumn	Urban area	6.82 (5.67–7.84)	1–2 (p<0.05) 1–3 (p<0.01)
Winter	Urban area	4.10 (3.56–5.11)	1–4 (p<0.05)
Spring	Urban area	7.15 (6.04–7.92)	
Summer	Urban area	5.61 (4.45–6.27)	
Autumn	Background area	4.95 (3.83–5.79)	
Winter	Background area	2.62 (1.98–3.24)	1–2 (p<0.05) 1–3 (p<0.05)
Spring	Background area	2.68 (1.87–3.46)	
Summer	Background area	3.10 (2.74–4.08)	

Table 3. Seasonal variations in DIBP concentration

Year season	Area	Median (Q25–Q75) ng/m ³	p
Autumn	Urban area	19.12 (18.09–19.89)	1–2 (p<0.00) 1–3 (p<0.01) 1–4 (p<0.00)
Winter	Urban area	6.11 (5.44–7.12)	2–3 (p<0.05) 2–4 (p<0.05)
Spring	Urban area	8.23 (7.33–8.94)	
Summer	Urban area	3.41 (2.18–4.57)	
Autumn	Background area	12.80 (11.45–13.67)	1–2 (p<0.00) 1–3 (p<0.00) 1–4 (p<0.01)
Winter	Background area	5.23 (4.42–6.57)	
Spring	Background area	3.42 (2.51–4.32)	
Summer	Background area	4.44 (3.69–5.18)	

Table 4. Seasonal variations in DEHP concentration

Year season	Area	Median (Q25–Q75) ng/m ³	p
Autumn	Urban area	12.92 (11.87–13.76)	1–2 (p<0.01) 1–4 (p<0.01)
Winter	Urban area	7.87 (6.52–8.44)	2–3 (p<0.00)
Spring	Urban area	13.88 (12.91–14.66)	3–4 (p<0.00)
Summer	Urban area	7.82 (6.46–8.22)	
Autumn	Background area	10.00 (9.41–11.06)	1–2 (p<0.05) 1–3 (p<0.01)
Winter	Background area	8.27 (7.61–9.08)	
Spring	Background area	6.83 (5.48–7.66)	3–4 (p<0.01)
Summer	Background area	9.41 (8.87–10.24)	

6.82 ng/m³ in autumn and 7.15 ng/m³ in spring, while in winter and summer they decreased to 4.10 and 5.61 ng/m³, respectively (p<0.05).

The observed spring peak of DEHP within the urban area (13.88 ng/m³) may be related to increased construction activity in the Snegovaya Pad area adjacent to the sampling point, which typically intensifies in spring. Municipal records for Vladivostok (public registry; available since 2018) confirm that several construction projects in the Snegovaya Pad area were authorized during the overlapping sampling interval (2018–2022). Thus, although the permit data support the likelihood that construction underlies the spring DEHP anomaly, this explanation remains provisional for the earlier portion of the sampling period (2014–2017). In the background area, maximum concentrations of DEHP were recorded in summer (9.41 ng/m³), which may be explained by sea breezes bringing pollutants from the mainland.

At the next stage of the study, the following multiple regression models were constructed to detail the effects of various factors and predict the accumulation of phthalic acid esters:

$$DBP = 8.6 - 0.71 \times H - 0.69 \times T - 0.64 \times WS + 0.62 \times AT \quad (1)$$

($R = 0.68$; Durbin–Watson test = 1.9; $p < 0.008$; $F = 16.8$)

$$DIBP = 12.42 + 0.74 \times AT - 0.72 \times T - 0.71 \times H - 0.61 \times WS \quad (2)$$

($R = 0.76$; Durbin–Watson test = 1.8; $p < 0.0017$; $F = 23.3$)

$$DEHP = 6.28 - 0.79 \times T - 0.77 \times H + 0.68 \times AT - 0.53 \times WS \quad (3)$$

($R = 0.79$; Durbin–Watson test = 1.84; $p < 0.001$; $F = 28.21$)

where H is the humidity (%), T is the temperature (°C), WS is the wind speed (m/s), AT is the vehicle traffic (vehicles/min).

The models take into account climatic and anthropogenic factors that had the greatest impact on the content of the studied phthalates in the monsoon climate conditions. The regression models were developed using the pooled dataset from the two sampling locations, which included all 693 samples collected across all four seasons (autumn, winter, spring, and summer).

Among the constructed models, the model for DEHP ($R = 0.79$) has demonstrated the greatest predictive power, where temperature, humidity, and automotive traffic were the key predictors. The Durbin–Watson test values for all models are within the acceptable range, which indicates the absence of autocorrelation of residuals. An important characteristic in all three models is that p-value is less than 0.05, and the level of Fisher coefficients are adequate, which indicates the statistical significance of the developed models and the possibility of their application.

Modern studies indicate the widespread presence of phthalates in the atmospheric air, including in remote regions and the regions with minimal anthropogenic impact, such as the seas and the Arctic region (Mi et al., 2023; Xie et al., 2007). At the same time, their concentration levels in different geographical zones vary depending on the intensity of the anthropogenic load, climatic and weather conditions, and the local ground features.

Among all phthalates, DEHP occupies a leading position in terms of detection frequency in studies of atmospheric air pollution. This is primarily due to its widespread use in industry, especially in the production of plastics, building materials, and packaging. Despite the legal restrictions, mass production of DEHP is not discontinued, but only transformed towards reducing its areas of use. Other phthalates, such as DBP and DIBP are used in a similar way. However, in recent years there has been a tendency to increase the share of industrial use of DIBP, which, in turn, is reflected by its increased concentrations in the environment.

A comparative analysis of the data obtained in the present study with the data published by other authors allows concluding that the level of atmospheric air pollution with phthalates within the urban territory of Vladivostok is intermediate compared to other regions. In particular, it was revealed that the average annual concentrations of phthalates in Vladivostok city are lower than in a number of industrially developed areas, such as for example the Okhla industrial zone in India, where the DEHP concentration reaches 25.446 ng/m³, while in Vladivostok it is about 10.39 ng/m³. At the same time, the content of DIBP in the air of Vladivostok is significantly higher than in the area in Okhla (7.17 and 6.08 ng/m³ in the city and on the island, respectively, versus 1.172 ng/m³ in Okhla) (Das et al., 2014). Hangzhou city in China has also recorded measurable levels of phthalates in the outdoor air, with concentrations in the particulate phase reaching 126 ng/m³ (Lu et al., 2023). In other Asian countries, phthalate concentrations range from 0.8 µg/m³ in Vietnam (Tran et al., 2017) to 6.2 µg/m³ in Japan (Takeuchi et al., 2014). At the same time, compared with megacities that do not have a pronounced industrial component, such as Paris, for example, where phthalate concentrations are significantly lower (0.211–0.33 ng/m³ for DIBP and 3.8–8.9 ng/m³ for DEHP in summer season), Vladivostok demonstrates a higher level of pollution (Teil et al., 2016). This fact suggests that in the context of phthalate air pollution, Vladivostok occupies an intermediate position between large industrial regions and urbanized areas with relatively low anthropogenic activity. Such status is due to both the scale of the urban industry and the natural and climatic conditions of the region.

Climate and weather conditions play a significant role in the variability of phthalate content in the outdoor air, especially in regions with pronounced seasonality. Vladivostok, located in the monsoon climate zone at the junction of the continent and the ocean, is characterized by significant seasonal fluctuations due to the complex orographic structure of the territory. This affects both the total phthalate content in the air and their distribution between the gas and solid phases. In most climatic regions of the world, researchers traditionally consider winter and summer seasons as most representative for identifying seasonal pollution dynamics. In moderate climate conditions, where winter and summer differ significantly in temperature and the nature of anthropogenic load, clear seasonal trends are identified in general: in summer, phthalate concentrations reach peak values, while in winter they decrease significantly (Ouyang et al., 2019; Teil et al., 2016; Zhu et al., 2016). On the one hand, such pattern is due to increased levels of solar radiation and automotive traffic intensity during the warmer months, and, on the other hand, to increased emissions from heating systems in winter season.

However, Vladivostok is characterized by a different climatic dynamics. Summer months are characterized by a combination of high temperature and humidity

(Veremchuk et al., 2018), which leads, on the one hand, to more intensive migration of phthalates from polymer materials, and, on the other hand, to increased degradation of these compounds due to both biotic and abiotic processes. Moreover, high humidity reduces the effectiveness of phthalate adsorption on the solid phase of the particles, which reduces their total content in the air. The sea winds prevailing in summer contribute to the transfer of pollutants from the city area towards the mainland. On the contrary, temperatures and humidity in winter are low, and air masses move from land to sea, which also prevents the accumulation of phthalates in the atmosphere. As a result, unlike in a number of other regions, no significant seasonal differences in phthalate concentrations were revealed in Vladivostok with the monsoon climate.

The highest levels of these substances were recorded in the autumn season, which is associated with climatic conditions that contribute to their accumulation in the solid phase of the air. It is at this time that is characterized by the relatively stable meteorological conditions, contributing to a decrease in the degradation rate of phthalates and an increase in their adsorption on aerosol particles.

In the context of phthalate pollution, special attention should be paid to the geographical location of Vladivostok. Its proximity to the sea facilitates constant exchange processes between seawater and the atmosphere, which is confirmed by current studies (Mi et al., 2023; Xie et al., 2007). In this case, the marine environment acts as a phthalate absorber, and the interphase transport rate and direction depend on weather conditions and the direction of prevailing winds.

Thus, based on the data obtained, it can be concluded that the concentrations of the most common phthalates, specifically DBP, DIBP, and DEHP in the atmospheric air of Vladivostok are lower than the concentrations typical for large industrial cities in Asia, but exceed the values typical for urbanized non-industrial areas in Europe. The space-time distribution of phthalate content is determined by a variety of factors, including climate features, terrain, air mass directions, and local anthropogenic load. The conducted statistical analysis made it possible to establish correlations between phthalate concentrations and climatic and weather parameters, as well as to identify their seasonal distribution features. Based on the collected data, multifactorial regression models were developed that allow predicting the levels of atmospheric air pollution with phthalates in the monsoon climate of Vladivostok, taking into account seasonal and weather fluctuations. The research outcomes are intended not only to fill the existing information gap, but also to provide scientifically sound ideas about the impact of specific climatic conditions of the coastal zone on the nature of chemical pollution of the atmospheric environment.

CONCLUSIONS

1. The content of three phthalates, specifically, dibutyl phthalate, diisobutyl phthalate, and diethylhexyl phthalate was revealed in the two studied zones. In both zones, DEHP accounts for about 50% of the total mass of phthalates, DIBP is in second place in terms of mass, while DBP is represented in the least amount.

2. Differences in concentrations were revealed between the two studied zones: the concentration of DIBP in the urban area is 18% higher than in the background area; the concentration of DBP in the city is almost twice as high as on the island; and the concentration of DEHP in the city is 21% higher than on the island. Concentrations

of DBP and DEHP in the urban area are higher than those in the background area, which is associated with a greater anthropogenic load in this area. However, no statistically significant differences in DIBP content were found between these two areas, which may be due to the same sources of this phthalate in both areas.

3. Correlations have been established between the concentration of detected phthalates and weather factors, namely a negative correlation with temperature, humidity, and wind speed, and a positive correlation with the intensity of automotive traffic.

4. The variability of phthalate concentrations in the atmospheric environment with a moderate monsoon climate of Vladivostok has been revealed depending on seasons of the year.

For DBP, the highest concentrations were observed in autumn, and the minimum concentrations (1.5–2 times lower) in both zones were observed in winter and summer seasons. Concentrations of DIBP in the urban area were high in spring and autumn seasons, while in the island area – only in autumn. The minimum concentrations (3–5 times lower) were observed in summer season. Maximum concentrations in DEHP were detected in spring and autumn seasons, while minimum concentrations (1.5 times lower) were observed in winter and summer in the urban area. The DEHP concentrations in the background area were maximum in summer and autumn, while minimum in spring season. ■

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THE SENSITIVITY OF MID- AND HIGH-LATITUDE TERRESTRIAL ECOSYSTEMS TO CLIMATE CHANGE

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INTRODUCTION

Modern climate change has become one of the most significant scientific and societal challenges of the 21st century. Rising air temperatures, altered precipitation patterns, an increased frequency of extreme weather events, the degradation of cryosphere systems, and the acceleration of transformations in terrestrial ecosystems are now being observed across nearly all regions of the globe. These changes are particularly pronounced in the mid- and high latitudes of the Northern Hemisphere where, however, warming rates exceed the global average and natural and socioeconomic systems are highly sensitive to environmental change.

Northern Eurasia is a key region for understanding the mechanisms, consequences, and future trajectories of climate-driven transformations. Its diverse landscapes, including forests, tundra, steppes, wetlands, mountains, and permafrost, play a crucial role in global biogeochemical cycles, water resources, biodiversity conservation, and climate regulation. Moreover, these territories support major industrial, agricultural, transportation, and urban systems, the sustainability of which increasingly depends on the ability of societies to adapt to rapidly changing climatic conditions.

The Special Issue titled «The Sensitivity of Mid- and High-Latitude Terrestrial Ecosystems to Climate Change» was conceived as a platform for interdisciplinary discussions about how natural and human-modified systems respond to climate variability and long-term climate change. This issue integrates studies of paleoclimatic reconstructions, hydrological modeling, ecosystem dynamics, the impacts of climate on biodiversity and public health, land system transformations, and adaptation strategies. Together, the contributions demonstrate the importance of combining retrospective analyses, contemporary observations, numerical modeling, and scenario-based forecasting to better understand how terrestrial ecosystems function and how vulnerable they are under changing climatic conditions.

This Special Issue is closely linked to the implementation of the large, interdisciplinary scientific project titled «Global Climate Challenges in Russia: Retrospective Analysis, Forecast, and Adaptation Mechanisms», which is supported by the Ministry of Science and Higher Education of the Russian Federation. The project aims to evaluate the long-term dynamics and contemporary trends of natural and socioeconomic systems in the context of climate change, as well as possible future pathways, and

to develop scientifically grounded adaptation strategies for societies and ecosystems. It integrates paleogeographic reconstructions, modern observational datasets, climate and hydrological modeling, remote sensing, and socioeconomic analysis to investigate climate impacts across diverse environmental zones in Russia, ranging from the Arctic to subtropical regions.

A major conceptual foundation of the project and this Special Issue is the understanding that contemporary climate trends cannot be fully interpreted without knowledge of past environmental variability. Instrumental observations only cover a relatively short period and do not encompass the full range of natural climate variability. Therefore, paleoclimatic archives, historical evidence, and long-term ecosystem reconstructions provide essential information for identifying analogues of future environmental states, evaluating the resilience of ecosystems and human communities, and improving the validation of climate models.

At the same time, modern climate change is no longer only a scientific problem. It directly affects water resources, food security, public health, biodiversity, energy systems, transportation infrastructure, and regional economic development. Climate adaptation is an increasingly urgent priority for national governments and regional administrations. Consequently, the studies in this issue address fundamental scientific questions and applied challenges related to sustainable development, environmental management, and climate adaptation.

The seven papers in this Special Issue demonstrate the variety of approaches and research directions that are currently influencing climate-related environmental studies in Northern Eurasia.

The paper by Medvedev, Stepanenko, and Ryazanova (2026) addresses a critical practical aspect of climate change research: how river runoff and hydrological systems respond to changing climatic conditions. In their paper entitled: «Simulation of the water regime of two large European Russian rivers under the conditions of modern climate in the TerM land surface model», they evaluate the TerM land surface model's ability to reproduce the hydrological regimes of the Vychegda and Oka rivers. Through their analysis of runoff dynamics, snow water equivalent, and spring flood characteristics, the authors demonstrate that physically based land surface models can accurately reproduce essential elements of the regional water balance under current climate conditions.

This study is significant because it highlights the opportunities and limitations of hydrological modeling in

large river basins. Proposed model improvements, such as accounting for artificial irrigation, calibrating infiltration parameters, and refining river network characteristics, significantly improve simulation quality. These advances are crucial for future evaluations of water availability, flood risks, and hydrological responses to projected warming in European Russia and other temperate regions.

The hydrological sensitivity to climate change is addressed in the paper by Georgiadi et al. (2026) titled «Changes in annual river flow in the Volga–Kama and Angara–Yenisei reservoir basins under contemporary and scenario global warming». The paper examines observed and projected changes in annual runoff and water availability in some of the most important river systems in Russia. Using observational datasets and CMIP6 climate model ensembles, the authors demonstrate substantial regional differences in the hydrological responses to global warming. The study shows that annual runoff in the Angara–Yenisei reservoir basins will likely increase under future warming scenarios, while changes in the Volga–Kama basin may vary considerably in magnitude and direction. The paper's analysis of water availability per capita is particularly important because it links hydrological changes with demographic and socioeconomic dynamics.

The results emphasize the growing importance of integrating climate projections into long-term water management, hydropower planning, and regional adaptation strategies. Reservoir systems in Northern Eurasia are critical to energy production, navigation, and water supply; their future operation will depend heavily on evolving climatic conditions.

The paleoclimatic dimension of ecosystem sensitivity is explored in the paper by Razjigaeva et al. (2026) titled «The Late Holocene Climatic Events on the Southernmost Russian Far East Coast: Variability Drivers». Using high-resolution paleoecological and geochemical analyses of the Lotus Lake record, the study reconstructs hydroclimatic variability over the past 2460 years. The paper provides important insights into the interactions among monsoon circulation, solar activity, Pacific Ocean processes, and regional hydrological dynamics. The authors demonstrate that the environmental evolution of Lotus Lake was strongly influenced by fluctuations in the East Asian summer monsoon and large-scale atmosphere–ocean interactions in the northwestern Pacific.

One of the study's major strengths is its demonstration of the complex spatial heterogeneity of hydroclimatic changes in the Pacific sector of Northeast Asia. Reconstructed environmental shifts during the Medieval Climate Anomaly and the Little Ice Age suggest that regional ecosystem responses were controlled by multiple interacting climatic drivers, such as changes in atmospheric circulation regimes and modes of climatic variability, rather than by temperature changes alone. The paper also emphasizes the importance of high-resolution paleoclimatic reconstructions in understanding abrupt environmental transitions and identifying natural analogues of ongoing climate change.

The issue of the impact of climate change on biological systems and public health is addressed in the contribution by Popov and Popova (2026) titled «Modeling the Potential Distribution of the *Ixodes pavlovskyi* Tick and Its Changes under Current Climatic Conditions». The expansion of vector-borne diseases is one of the most serious ecological and public health consequences of contemporary climate change. Using the MaxEnt modeling approach, the authors reconstruct the climatic range of *Ixodes pavlovskyi* for three periods spanning from 1961 to 2020. Their study shows

that warming temperatures have already contributed to a significant expansion of suitable habitats for the species, especially in Siberia. Identifying annual mean temperature and precipitation seasonality as dominant controlling variables emphasizes the close relationship between climate and vector ecology.

Importantly, the paper goes beyond a purely biogeographical analysis by emphasizing the practical implications of shifting species ranges for epidemiological monitoring, veterinary management, and adaptation planning. The findings underscore the necessity of integrating ecological forecasting into public health strategies in the face of rapid environmental change.

Another dimension of the impacts of climate change is represented by the paper by Szwed (2026) titled «The Changing Climate of Kielce: Insights from Extended Meteorological Analyses». Using long-term meteorological observations from 1966 to 2023, the study reveals significant warming trends in the Świętokrzyskie region of central Poland. The results reveal increasing air temperatures and substantial transformations in snow cover, heat wave frequency, and precipitation variability. Of particular note is the documented decline in snow cover duration and thickness, which has important implications for regional hydrology, agriculture, ecosystems, and urban infrastructure.

This paper clearly illustrates how regional climate studies can provide information that can be directly applied to adaptation planning. The observed increase in compound climate extremes, including simultaneous heat waves and droughts, demonstrates the growing vulnerability of regional socio-ecological systems. Therefore, the study contributes to the broader understanding of how global climate change manifests at local and regional scales.

The socio-economic and policy dimensions of climate change are explored in the paper by Klimenko et al. (2026) titled «History versus Aspirations: Carbon Neutrality Postponed by Several Decades». The study addresses a central question of contemporary climate policy: Can major developing economies achieve their declared carbon-neutrality targets within the proposed timeframes? By analyzing energy systems, land use, decarbonization trajectories, and carbon capture capacities in nine major developing economies, the authors conclude that current decarbonization rates and carbon capture technology deployment may be insufficient to achieve carbon neutrality within the declared timeframes. The paper emphasizes the substantial inertia in energy, industrial, and agricultural systems and discusses the growing importance of adaptation measures alongside mitigation efforts in future climate policy.

The study raises important questions about the feasibility of current climate strategies, the technological and economic challenges of rapid decarbonization, and the role of adaptation planning in the context of ongoing climate change. This discussion contributes to the broader international debate on the interaction between mitigation and adaptation approaches in climate policy.

Finally, the paper by Matasov et al. «Historical Land Systems of Russia: Trends, Biases, and Gaps in the Literature» (2026) provides an important meta-analysis of land system science research in Russia. Through a systematic review of 210 peer-reviewed studies, the authors identify significant geographical and thematic imbalances in historical land use research. The paper reveals that despite their major significance for global environmental change research, large regions of Siberia, the Arctic, and the Russian Far East remain poorly studied. The paper also highlights the

methodological limitations associated with the insufficient integration of historical datasets, remote sensing, and multi-scalar analysis.

This contribution is especially valuable because it addresses the scientific infrastructure of climate-related research itself. By identifying gaps in data accessibility, international visibility, and methodological integration, the paper outlines priorities for the future development of land system science in Russia and northern Eurasia. The paper emphasizes the importance of interdisciplinary approaches combining environmental history, remote sensing, geography, ecology, and socio-economic analysis.

Taken together, the papers in this Special Issue reveal several common themes.

First, climate change in Northern Eurasia affects multiple systems simultaneously, including hydrological, biological, cryospheric, and socio-economic systems. Understanding these interactions requires interdisciplinary approaches that can integrate observations, modeling, paleodata, and applied assessments.

Second, regional responses to climate change are highly heterogeneous. Even within relatively similar climatic zones, ecosystem and hydrological responses may differ substantially depending on local environmental conditions, circulation patterns, land use, and socioeconomic factors.

Third, long-term perspectives are essential. Paleoclimatic reconstructions and historical analyses provide critical insights into ecosystem resilience, rates of environmental transformation, and the mechanisms driving climatic variability.

Fourth, adaptation emerges as a central challenge throughout the issue. Studies demonstrate that climate change is already influencing water resources, public health, biodiversity, energy systems, and land use. Effective adaptation therefore requires integrated scientific knowledge that bridges the natural and social sciences.

The Special Issue highlights the growing importance of advanced methodologies in climate research. Numerical modeling, remote sensing, paleoecological analysis, species distribution modeling, and large climate model ensembles are forming an increasingly important basis for quantitative assessments of ecosystem sensitivity and future environmental risks. At the same time, the contributions remind us that models and projections must be continuously validated against observational and historical evidence.

The editors hope this collection of papers will encourage further interdisciplinary collaboration among climatologists, geographers, ecologists, hydrologists, and social scientists. Addressing modern climate challenges requires improved scientific understanding and effective communication between science, policy, and society.

As climate change accelerates, Northern Eurasia will continue to play a critical role in the global climate system and in international discussions on adaptation, mitigation, biodiversity conservation, and sustainable development. The vast terrestrial ecosystems, water resources, cryosphere, and socio-economic systems of the region provide major vulnerabilities and significant opportunities for developing adaptive responses to environmental transformation.

We sincerely thank all the authors for their valuable contributions to this special issue and the reviewers for their thoughtful comments and constructive recommendations. We are also grateful to the editorial team for their support in preparing this issue.

We hope the studies presented here stimulate further research on the sensitivity, resilience, and adaptive capacity of terrestrial ecosystems under changing climatic conditions. We also hope they contribute to developing scientifically grounded strategies for sustainable environmental management in Northern Eurasia and beyond. ■

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HISTORY VERSUS ASPIRATIONS: CARBON NEUTRALITY POSTPONED BY SEVERAL DECADES

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ABSTRACT. Here, we use modeling and literature assessments to quantify the prospects for achieving carbon neutrality by nine major developing economies (China, India, Indonesia, Brazil, Iran, Saudi Arabia, Turkey, Mexico, and South Africa). We examine the structure of energy consumption, electricity generation, and land use in these countries. Scenario estimates of the dynamics of carbon indicators of the world's leading economies at global and subglobal scales based on a historical approach have been developed.

It is shown that the current rate of decarbonization and the development of the carbon capture and storage industry in the studied countries is not sufficient for these countries to fulfill their obligations to achieve carbon neutrality in 2050-2070 – this goal cannot be attained before the end of the century. The key challenge in achieving the carbon neutrality is the rapid, large-scale deployment of the carbon capture and storage technologies in all possible forms. Of the countries studied, however, only China and Brazil have their capabilities to store carbon for more than a century.

Although climate change occupies practically a leading place in the global agenda, the actual results of efforts in this area are far from the declared ones, and the climate warming can no longer be kept within 1.5°C. The core problem is to minimize the residence time for the global climate system in the dangerous zone (with a temperature overshoot above 1.5°C), which will require the emergence of the world economy with negative greenhouse gas emissions.

KEYWORDS: developing countries, energy, greenhouse gases emissions and absorption, carbon neutrality, scenarios

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INTRODUCTION

The year 2023 became the hottest year in the history of instrumental observations and finished with an outstanding record for the GMT, exceeding (according to CRU data¹) the pre-industrial (1850-1900) level by 1.46°C. At the same time, the previous record of 2016 was exceeded by 0.17 °C at once, a huge margin at the planetary level, which is a unique event in the entire era of instrumental observations and causes serious concerns among the global scientific community (Schmidt 2024). In the year 2024, the record-breaking succession continued, and a unique 13-month (from June 2023 to June 2024) series of monthly temperature maximums was recorded.

Finally, contrary to the expectations, the year 2024 was even hotter than the year 2023, having the annual mean temperature 1.55°C higher than the pre-industrial level, thereby overcoming the first critical threshold set by the Paris Agreement. And although this is only the temperature of one year, this fact is an alarm signal and a warning message to the world community that dangerous levels of warming are very close. In spite of the fact that the strong El Niño², which was largely responsible for the temperature surges in 2023 and 2024, ended in May 2024, the temperature remains at the same level close to the record marks in the first nine months of 2025. The climatically significant average global temperature anomaly over the decade (2015-2024) attained 1.26°C, and thus the world was about to reach

¹CRU Global temperature dataset HadCRUT (<https://crudata.uea.ac.uk/cru/data/temperature/>)

²El Niño is an irregular phenomenon occurring every 3-7 years, which increases water temperature in the tropical Pacific and is the main cause of interannual fluctuations in the global average temperature

the 1.5°C threshold, which is clearly considered by the world community as an extremely undesirable event (King et al. 2023). Should a warming rate of about 0.2°C per decade achieved over the last 30 years be maintained, the critical threshold may be crossed as early as the mid-2030s. In the current situation, the best and still feasible scenario is the temporary overshoot of the 1.5°C threshold, attainment of the warming peak followed by the temperature decrease as a result of the effective implementation of the initiatives of the Glasgow (2021) and Dubai (2023) summits (Klimenko et al. 2022a) or the implementation of low demographic scenarios (Klimenko et al. 2022b). This overshoot represents a serious threat to the stability of the global climate system, and the world community already poses the problem to minimize the residence time in this potentially devastating elevated temperature zone.

Over the past thirty years, the world community has made considerable efforts to control the hazardous global warming, and the core of these efforts is the measures to slash GHG emissions, the purpose of which is to achieve so-called carbon neutrality (the term “carbon neutrality” used in the paper refers only to anthropogenic activities and means the balance of emissions and sinks into natural or anthropogenic reservoirs of man-made greenhouse gases and other climate active matters – aerosols etc., – recalculated to carbon dioxide through global warming potential) (Fragkos et al. 2021, Das et al. 2023).

In our recent works (Klimenko et al. 2023a, Klimenko et al. 2024a, Klimenko et al. 2024b), we examined the capabilities of the world’s leading economies and Russia, which can be employed to solve the critical climate protection problem – achieving carbon neutrality by national economies by 2050–2060. We have demonstrated that, despite the great potential for reducing greenhouse gas emissions in various sectors of the economy, both Russia and OECD countries face serious difficulties in solving the problems in question.

In this paper, we examine whether the developing countries, which will become the backbone of the world economy in the immediate future, will be able to achieve their goals within their own timeframes. According to the WRI³, the selected nine countries (Table 1) are currently responsible for almost half of global greenhouse gas emissions, and their development pathways are critical to the feasibility of implementing the Paris

Agreement on limiting the global warming to “well below 2°C and preferably within 1.5°C”.

It follows from Table 1 that all these countries, except Iran and Mexico⁴, have put forward the ambitious targets of attaining carbon neutrality in 2050–2070 with a peak of GHG emissions occurring before 2030.

The aim of this paper is to find out how great the chances are of these countries implementing such impressive plans.

HISTORY AND CURRENT STATUS

All selected countries are characterized by a considerable increase in GHG emissions in recent decades (Fig. 1), but in the last 8–10 years, almost half of them (Iran, Saudi Arabia, Mexico, and South Africa) demonstrate its stabilization. The growth rate of specific (per capita) emissions is much lower, and stabilization of this indicator is already seen in all countries, while in Brazil, Saudi Arabia, and South Africa, it even decreases.

Terrestrial biota (LULUCF, Fig. 2) can be either a net sink (such as in China and India, where increased reforestation exceeds forest loss due to logging and fires) or a net source of GHGs (Brazil and Indonesia, where ongoing large-scale tropical deforestation is not compensated for by reforestation, including planting and natural tropical regrowth). Carbon dioxide emissions from the LULUCF sector have accounted for almost 50% in Indonesia over the past 20 years and about 30% of the total national emissions in Brazil.

The emission rate of the main greenhouse gas – carbon dioxide – is controlled essentially by the total energy consumption (in all sectors of economy – power generation, industry, transportation etc.) and the structure of the energy mix (Fig. 3). The cement production (referred only to chemical process and do not include the fuel combustion to produce heat for this process) in the above-listed countries accounts for a maximum of 5% of the total CO₂ emissions.

As with all rapidly developing national economies, the studied countries demonstrate a high growth rate of energy consumption (Fig. 4a). Thus, over the 1990–2023 period, the

Table 1. Voluntary commitments to reduce net greenhouse gas emissions by UNFCCC parties⁵

UNFCCC party	Reference year	Emissions in % to the reference year		Attainment of	
		in 2030	in 2050	peak emission	carbon neutrality
Brazil	2005	47		2008	2050
India	2005	100	62	NA	2070
Indonesia	2010	95	50	2030–2035	2060
Iran	2010				
China	2005	175	55	before 2030	2060
Mexico	2000	65	50		NA
Saudi Arabia	2020	61		2016	2060
Turkey	2012	216			2053
South Africa	2010	70–80			2050

³ WRI Greenhouse gas emissions database (<https://www.wri.org/data/climate-watch-cait-country-greenhouse-gas-emissions-data>)

⁴ Iran makes targets to limit GHG emissions and achieve climate neutrality depending on lifting of economic sanctions. Mexico has no net-zero or any other long-term climate neutrality targets.

⁵ UNFCCC Nationally Determined Contributions (<https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs>)

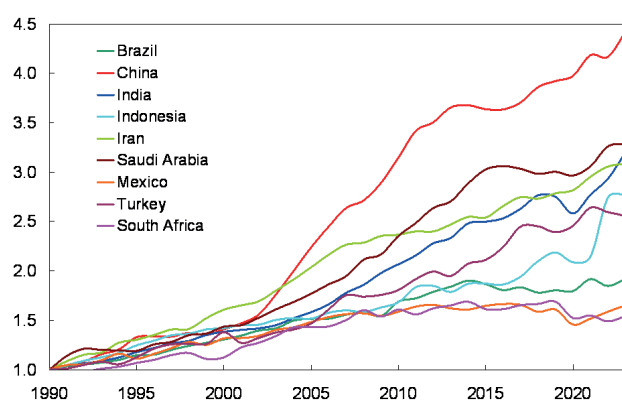


Fig. 1 a

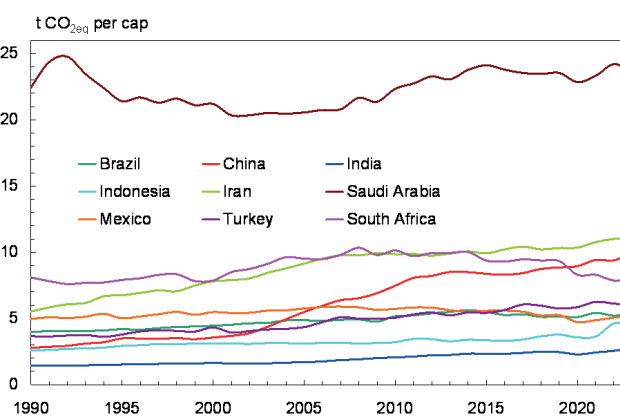


Fig. 1 b

Fig. 1. GHG emissions (excluding LULUCF) - gross relative to 1990 levels (a) and per capita (b) (according to WRI3 and UN⁶ data)

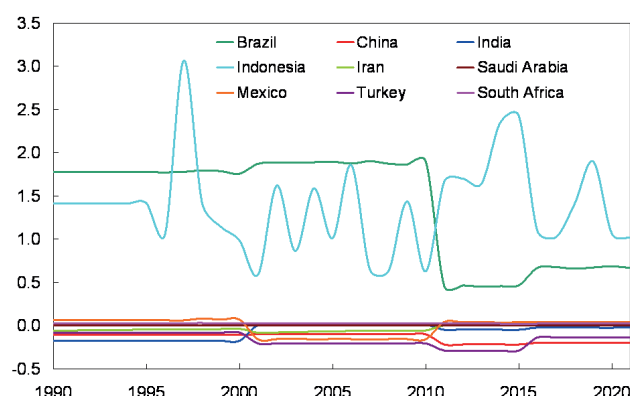


Fig. 2

Fig. 2. Ratio of GHG emission/sink from LULUCF to industrial emissions in 1990–2021 (according to WRI data³)

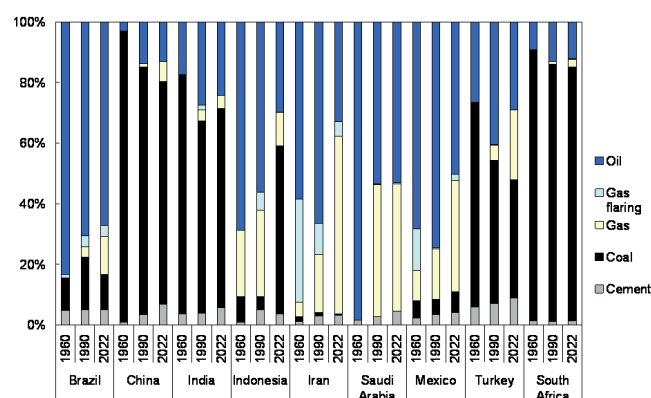


Fig. 3

Fig. 3. Structure of CO₂ emissions from combustion of various fuel types and cement production (according to WRI data³)

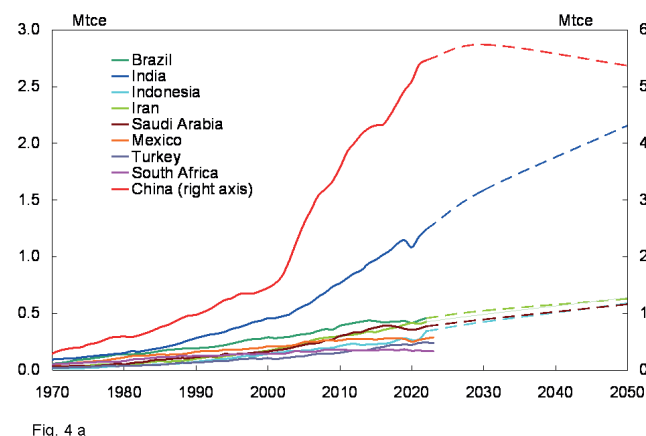


Fig. 4 a

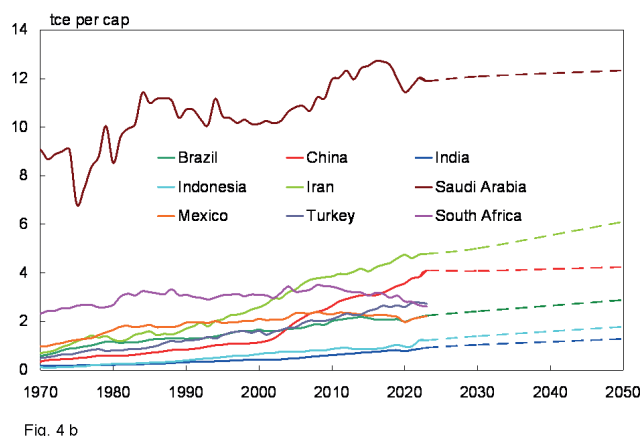


Fig. 4 b

Fig. 4. Primary energy consumption (fossil fuels, hydro- and nuclear energy, and renewables combined) – gross (a) and per capita (b) tce values (according to the historical data⁷, UN data⁶ and IEA STEPS scenario⁸)

gross consumption of primary energy increased by about 5.5 times in China, by about 4–4.5 times in India, Indonesia, and Iran, and by 2.5–3.5 times in Brazil, Turkey, Mexico, and Saudi Arabia.

The dynamics of specific energy consumption indicators (Fig. 4b) look less pronounced. Stabilization and even some decrease of this characteristic have been observed in China, Brazil, Saudi Arabia, Mexico, and South

Africa in recent years, while its growth rate declined considerably in India, Indonesia, Turkey, and Iran.

Considerable differences are seen in the structure of the fuel mix (Fig. 5a).

The power industry in China, India, Indonesia, and South Africa is predominantly based on coal. At the same time, over the past 60 years, the share of this fossil fuel in the national energy balance of China and India steadily decreased to about

⁶World Population Prospects 2024. New York: United Nations, Department of Economic and Social Affairs, Population Division.

⁷Statistical Review of World Energy 2024. London: Energy Institute, 2024.

⁸The latest forecast from the IEA World Energy Outlook 2024 (Paris: International Energy Agency, 2024) examines two scenarios – STEPS, which is based on the applicable decarbonization programs of national economies, and APS, which assumes that national targets under the Paris Agreement are achieved as scheduled and in full.

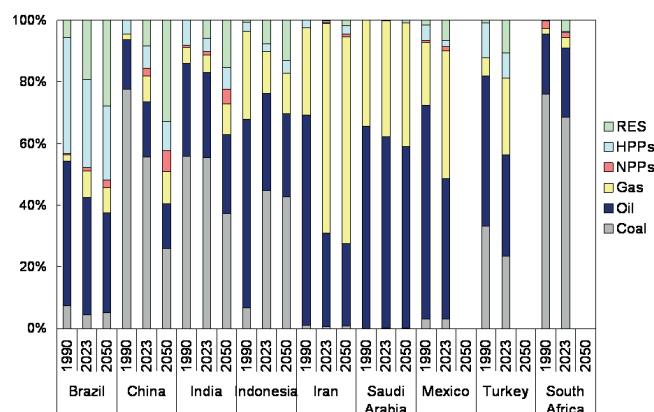


Fig. 5 a

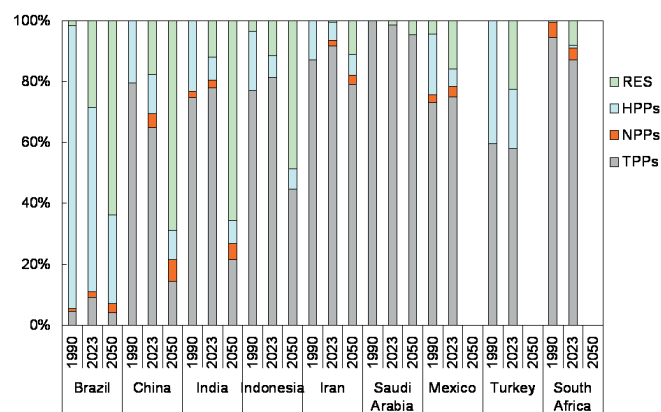


Fig. 5 b

Fig. 5. Structure of energy consumption (a) and power generation (b) (according to the historical data⁷ and STEPS scenario⁸)

55% in 2022, while in Indonesia, on the contrary, it has grown to 45%. Carbon-free energy sources (such as HPPs, NPPs, and RES) account for 5-15% of the total energy consumption in these three countries, and their share of the energy balance grows continuously. This trend will receive a powerful boost in the coming decades – thus, China, being the absolute world leader in the deployment of carbon-free energy sources, intends to produce 50% of electricity using renewable energy sources (including HPPs) already by 2028.

The main source of energy in oil- and gas-producing Iran and Saudi Arabia is hydrocarbons, and a marked trend of transition from oil towards gas, whose percentage was almost 40% in Saudi Arabia and 70% in Iran by 2022, has been observed over the past 60 years. Currently, carbon-free energy sources in these countries contribute very little to their overall energy balance.

Brazil has the most balanced low-carbon energy complex, with almost half of its energy consumption currently covered by hydropower, the share of oil having decreased to 40%, the share of gas having increased to 10%, while coal accounts for a maximum of 5% of the total energy demand.

In the electric power industry (Fig. 5b) the situation is even more unusual. In Iran and Saudi Arabia, almost all electric power is generated at TPPs fired with natural gas and fuel oil. In India and Indonesia, about 20% of electricity generation comes from carbon-free sources (HPPs, NPPs, and RESs), and the rest is covered by coal-fired TPPs. In China, more than a third of power plant output is generated without burning fossil fuels; thermal power generation predominantly uses coal as fuel. In Turkey, HPPs and RESs provide 20% of the total electricity generation, while Brazil receives almost 90% of its electricity from HPPs, RESs, and NPPs, making it one of the world's leaders in carbon-free electricity generation.

The volume and structure of energy consumption determine the level of carbon dioxide emissions in the power industry (Fig. 6). Gross CO₂ emissions in the examined countries (Fig. 6a) are growing at a lower rate than the energy consumption does (Fig. 4a), which is explained by an increase in the percentage of power generation using low-carbon (natural gas) and carbon-free (HPPs, NPPs, and RESs) energy sources in the energy balances.

As a result, the specific emission of carbon dioxide (per unit of consumed primary energy, Fig. 6b), called carbon intensity or carbon intensity of energy consumption, decreases in all studied countries.

For instance, in Brazil, this process occurred intensively as early as the 1970s due to the construction of large HPPs, as a result of which the energy intensity of its power industry has been at a very low level of 1.1 t CO₂/tce for over 40 years, which is much lower than in developed economies of the EU or the USA. Iran and Saudi Arabia have been continuously reducing the carbon intensity of their energy consumption during the last decades by replacing oil with natural gas in their energy balance, thereby reducing the specific emissions from 1.9 t CO₂/tce in 1980 to 1.55 t CO₂/tce in 2023, which is much lower than the current global average value of 1.75 t CO₂/tce.

China also systematically reduced specific emissions in its national power industry, mainly by commissioning large HPPs and NPPs in the period before 2005 and at an even higher pace due to the large-scale construction of solar and wind power plants in the last two decades. This reconstruction of the power industry reduced the specific emissions from 2.6 t CO₂/tce in 1970 to 2.35 t CO₂/tce in 2005 and 1.9 t CO₂/tce in 2023.

No visible progress in cutting down specific emissions is typical for the power industry in India, Indonesia, and South Africa, where the share of coal is still great, and the rate of

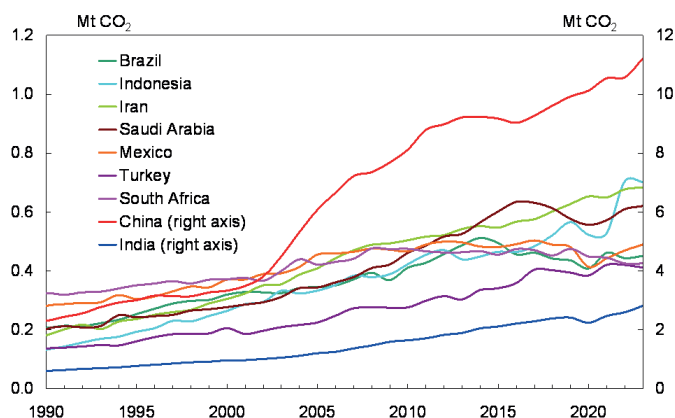


Fig. 6 a

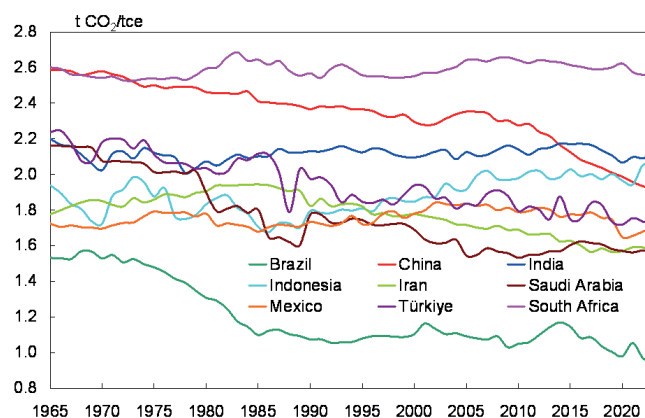


Fig. 6 b

Fig. 6. Carbon dioxide emissions in the energy sector – gross values (a) and values per unit of primary energy consumption (b) according to historical data⁷

introduction of carbon-free energy sources falls far short of the global average value.

Fig. 6b demonstrates that the power industry is a very inertial sector of the economy, and decades are always required to make substantial progress here.

The land use sector is even more inert than the power industry and is just as crucial for covering the basic needs of the population. FAO data collected since 1961 (Fig. 7a) have demonstrated a slower growth of agricultural land areas, including arable land, in all studied countries, and in tropical countries (Brazil and Indonesia) this is caused by deforestation. Forested areas increase in India, Iran and especially in China, including due to large-scale forest plantations (Fig. 7b). Reforestation activities in Brazil and Indonesia are still in an embryonic state and cannot yet compensate for deforestation, often illegal.

As a result, forest areas are increasing only in Turkey, India, China, and Iran (by 14%, 15%, 20% and 40% compared to 1990, respectively) and continue to decrease in South Africa, Mexico, Brazil, and Indonesia (by 6%, 7%, 15% and 22% compared to 1990, respectively) (Fig. 8a).

Another essential trend is the decrease in the specific arable area per capita (Fig. 8b). The development of

agricultural technologies means that today, providing food requires a smaller area of cultivated land, specifically 0.1-0.2 hectares per person, which is 2-3 times smaller than the area needed 60 years ago.

Thus, the current state of the power industry and land use in the studied countries as sources of greenhouse gases has the following main features:

- continued growth in gross energy consumption against the background of stabilization (and even a decline in certain countries) of its specific indicators (per capita);
- lower carbon intensity of energy consumption due to the transition to low-carbon (natural gas) energy sources and rapid development of carbon-free (HPPs, NPPs, RESs) energy sources;
- larger area of agricultural land (including arable land) with its smaller area per capita due to the enhancement of agricultural technologies;
- formation of a trend towards enhanced reforestation, which in some countries (China, India) already exceeds the scale of deforestation, thereby increasing the area of forests – the main absorber of carbon dioxide.

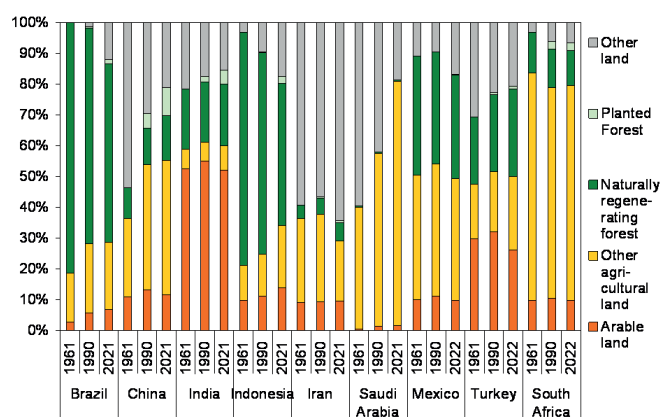


Fig. 7 a

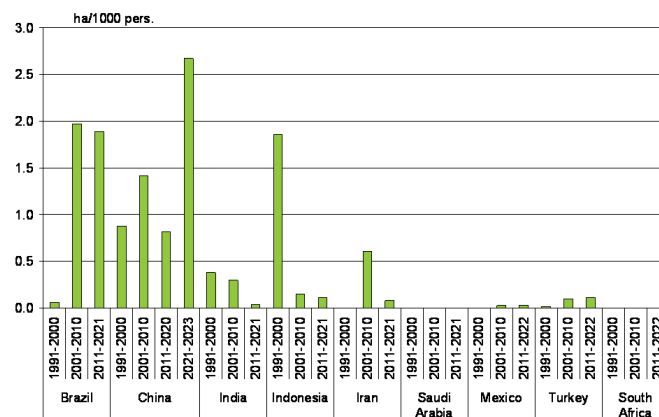


Fig. 7 b

Fig. 7. Structure of land use (a) and forest plantations area per capita (b) (according to FAO data⁹)

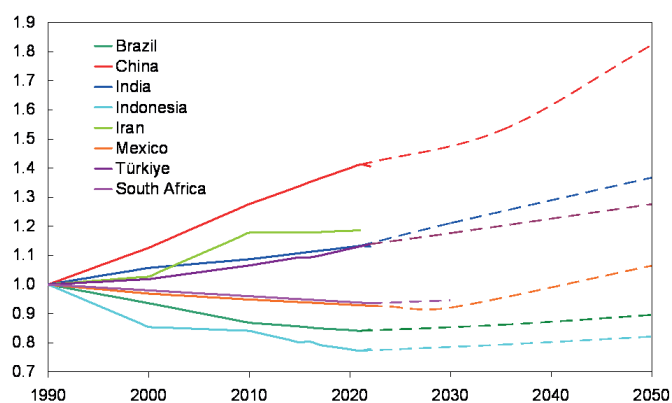


Fig. 8 a

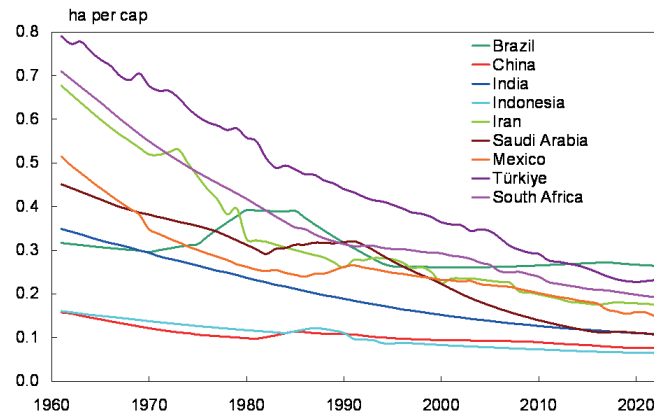


Fig. 8 b

Fig. 8. Forest area relative to 1990 levels (a) and arable land area per capita (b) according to historical FAO data⁹ and national plans^{10,11,12,13,14} (Gonzalez-Abraham et al. 2024)

⁹FAO Food and agriculture database FAOSTAT (<http://www.fao.org/faostat/en/#data>)

¹⁰China sets ambitious forestry development goals for 2050 (<https://bioenergyinternational.com/china-sets-ambitious-forestry-development-goals-2050/>)

¹¹India's long-term low-carbon development strategy. Submission to the United Nations Framework Convention on Climate Change. (2022) New Delhi: Ministry of Environment, Forest and Climate Change. Government of India.

¹²Indonesia Long-Term Strategy for Low Carbon and Climate Resilience 2050. 2021. 156 pp. https://unfccc.int/sites/default/files/resource/Indonesia_LTS-LCCR_2021.pdf

¹³Saudi Green Initiatives. (<https://www.greeninitiatives.gov.sa/about-sgi/sgi-targets/reduce-carbon-emissions/>)

¹⁴2030-2050 Vision. The future of forests and agriculture in Brazil / General edition: F. Macedo, M. Campanili. Brazilian Coalition on Climate, Forests and Agriculture, 2018

SCENARIOS

To assess the prospects for decarbonization of the economies of developing countries, the relationship between the rate of change in specific GHG emissions per capita and GDP per capita was analyzed (Fig. 9). The initial data used were GHG emission indicators from WRI (excluding LULUCF) and IMF economic data. For this study, 130 countries with national GHG emissions above 10 million tons of CO_{2eq}/year each were selected; countries with unstable political situations (Sudan, Syria, Somalia, Yemen) were excluded.

As expected, low GDP per capita values do not promote lower carbon intensity of the economy – countries with the specific GDP below approximately USD 10,000 per person are essentially characterized by greater specific GHG emissions per capita. Here, the top priority problem for the government of these countries is to fight poverty, while environmental issues and, in particular, emission control problems inevitably take second place. At the same time, on an increase of the nominal GDP above a threshold of USD 14 thousand per person (this value coincides with the conditional boundary between rich and poor countries according to the IMF terms), the rate of specific GHG emission reduction depends nearly linearly on the specific GDP – a linear dependence of the reduction rate of specific GHG emissions on the specific GDP is observed – rich countries can already afford implementation of such activities and readily finance the energy transition and decarbonization of the economy.

To assess the potential for decarbonization in the studied countries in the coming decades, the medium UN population scenario (UN 2024) and the long-term

economic forecast of the Goldman Sachs group (Daly et al 2022) were employed within the scope of the proposed approach. According to the IMF (Fig. 9a), at present only Saudi Arabia has a specific GDP above US\$14 thousand per person. The long-term projections (Daly et al 2022) suggest that China and Turkey will cross this threshold by 2030, Brazil and Mexico by 2040, Iran in 2050, and Indonesia and South Africa only after 2060. India will reach this level only by the end of this century due to still uncontrolled population growth. The obtained estimates of the dynamics of specific emissions per capita are shown in Fig. 10, and the gross emissions are presented in Fig. 11.

The results of the calculations demonstrate that, with the current trends in the field of climate protection, only China and Brazil would be able to achieve carbon neutrality by the end of the century, but with a long delay of 20-40 years relative to the declared deadline. To achieve this, China will have to maintain the record high level of energy decarbonization achieved over the past 15 years, and Brazil will have to completely abandon further severe deforestation of its forests and gradually harmonize its forestry practices with those applicable in other South American countries (FAO 2020; Harris et al. 2021; Houghton and Castanho 2023). Today Brazil seems to remain the only major country that can achieve carbon neutrality solely through the full activation of its biological potential without using CCS technologies. All other countries cannot attain carbon neutrality even by 2100, not to mention earlier dates, since GHG emissions in the economy are not compensated for by the growth in the absorption capacity of forest areas. Current efforts are clearly insufficient – this

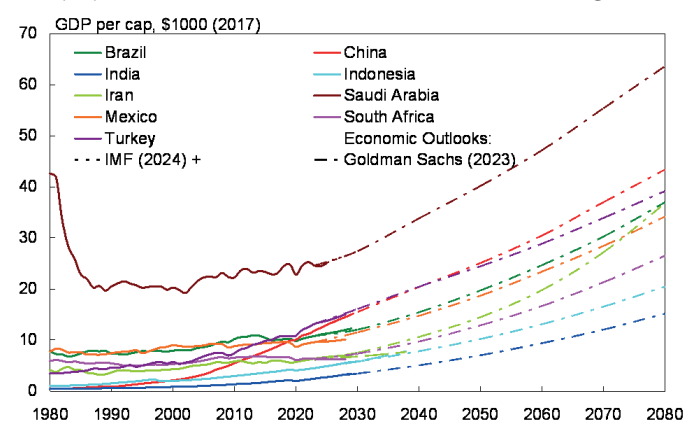


Fig. 9 a

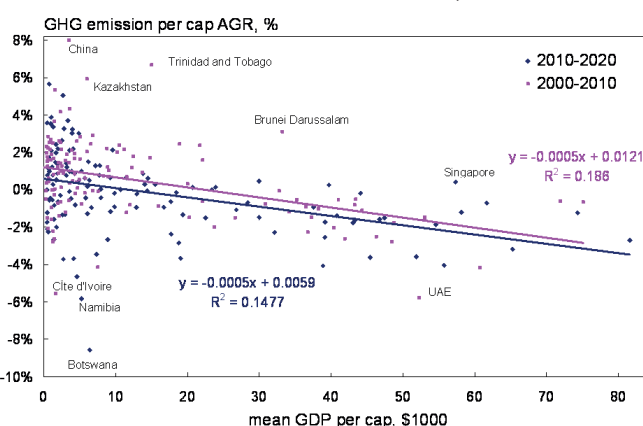


Fig. 9 b

Fig. 9. Constant price GDP per capita (IMF data, Daly et al 2022) (a) and its relationship with the rate of change of GHG specific emission per capita (according to IMF¹⁵ and WRI³ data) (b)

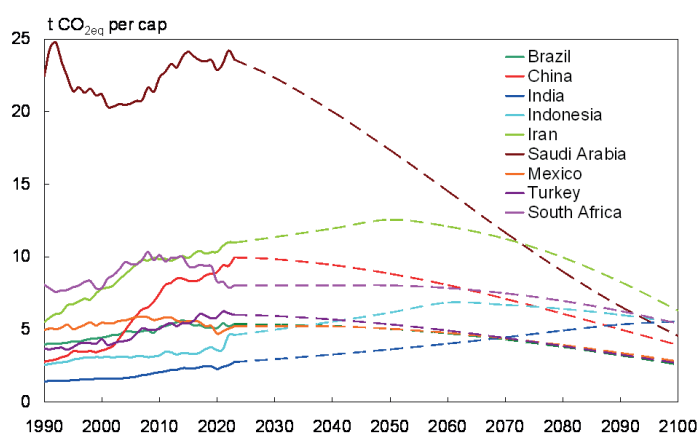


Fig. 10. GHG specific emission per capita in developing countries – history based on WRI data³ and projections of this study

¹⁵IMF Economic Outlook database (<https://www.imf.org/en/Publications/WEO/>)

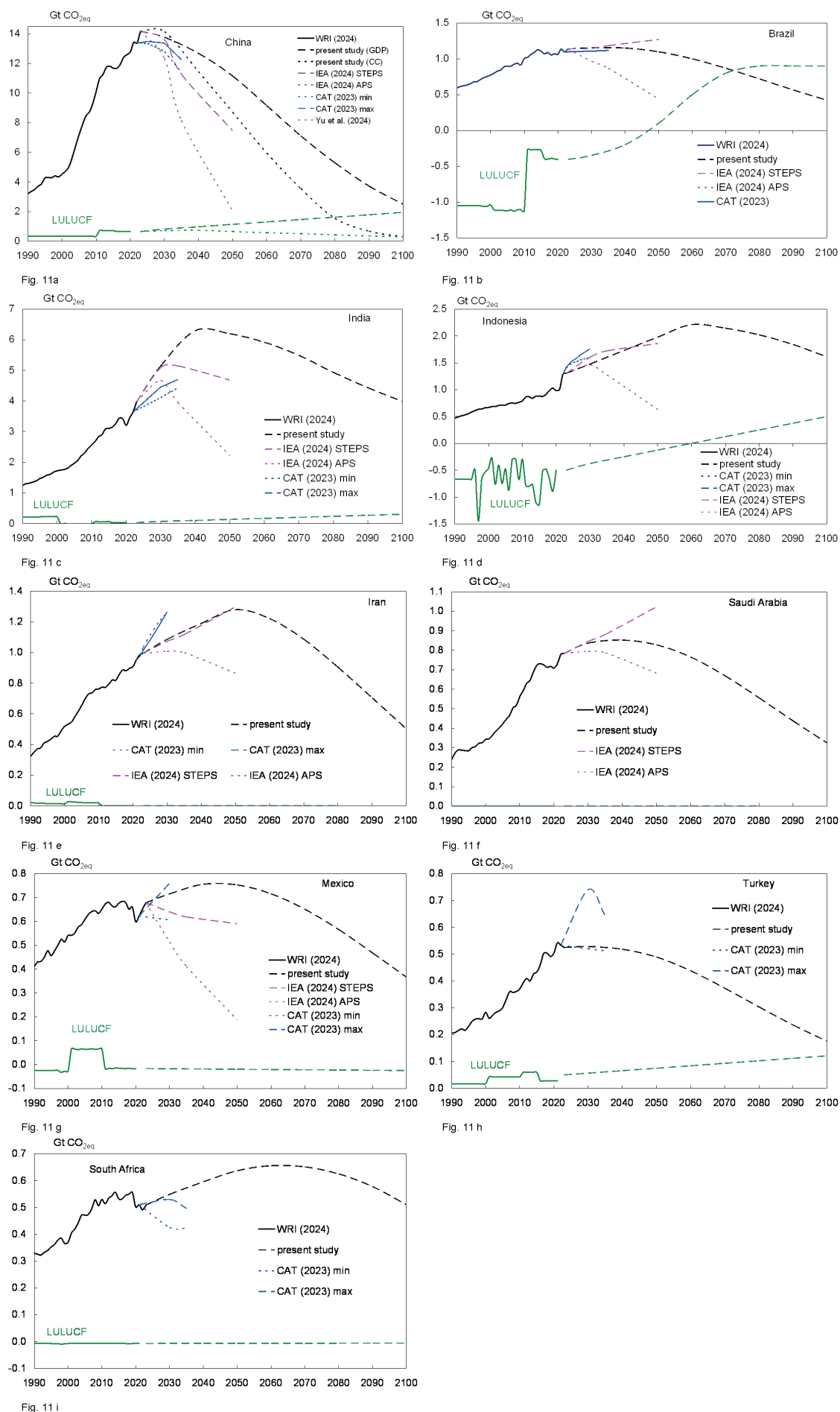


Fig. 11. Dynamics of gross GHG emissions (excluding LULUCF) and LULUCF net sinks based on WRI data³ and results of the calculations in this study, as well as IEA⁸ and CAT¹⁶ scenarios in China (a), Brazil (b), India (c), Indonesia (d), Iran (e), Saudi Arabia (f), Mexico (g), Turkey (h) and South Africa (i).

¹⁶<https://climateactiontracker.org/>

will become completely obvious in just five years, when it becomes clear that at the turn of 2030, China, Brazil, and Saudi Arabia will most likely locate themselves on a plateau of emissions, without having even begun to really reduce them, and India, Indonesia, and Iran will increase their emissions by another 15-20%. The consistent failures of many countries to implement climate protection plans generally arise from the fact that the expected rates of transformation of highly resistant areas of human activities, particularly the power industry, seem to exceed the capabilities of these countries shaped by their historical experience.

Nevertheless, the potential for reducing GHG emissions in some of the examined economies is quite high: by 2080, GHG emissions will decrease by 60% compared to 1990 levels in China, by 50% in Saudi Arabia, and by 30% in Brazil and Iran. India and Indonesia, due to continued population growth and lagging economic development, will continue to increase their GHG emissions until the second half of the century, remaining their main emitters.

The capabilities of increasing carbon absorption by forests are also very limited. Despite ambitious plans of China¹⁰ (Yu et al. 2024), India¹¹, Indonesia¹², Saudi Arabia¹³, and Brazil¹⁴, Mexico (Gonzalez-Abraham et al. 2024) (see Fig. 7) to increase forest areas in the coming decades, they will clearly be insufficient to offset large residual emissions everywhere except Brazil. Moreover, all countries with large forest areas, with the sole exception of China, face stubborn resistance from business and widespread violations of forest conservation laws.

Thus, the only solution to the problem of carbon neutrality for these countries is a development of CCS

technologies (Filippov et al. 2022, Kök 2015, Vourliotakis et al. 2024, Kearns et al. 2017, Collaborating 2024). However, current estimates of geological rock resources for CO₂ storage (Table 2) indicate that only Brazil has sufficient capacity, as it is the only country capable of storing its emissions at their current level for hundreds of years. This indicates that within the horizon of the next few decades, when, in fact, it is planned to achieve carbon neutrality, only China has promising plans for implementing CCS projects of sufficient capacity (Table 3).

The obtained calculation results demonstrate that none of the studied countries, except Brazil, can achieve carbon neutrality within the anticipated timeframe without widespread use of CCS technologies, since lower GHG emissions in the economy are not compensated for by a higher absorption capacity of forest plantations. At the same time, we should bear in mind that the intensity of the global biotic sink has a natural maximum of 6-9 Gt CO₂/year and may begin to decline as early as the middle of this century (Klimenko et al. 2020, Gidden et al. 2019).

The implementation of the decarbonization policy in the economies of the studied countries will reduce the GHG emissions by 2080, compared to the 2020 level, by 90% in China, 50% in Saudi Arabia, and 30% in Brazil and Iran. Continued high population growth rates and low levels of economic development in India and Indonesia will continue to increase GHG emissions, which will exceed the current levels by 1.2 and 1.7 times, respectively, by 2080.

Carbon capture by terrestrial ecosystems also has its limits. Although impressive plans of China, India, Indonesia, and Brazil to increase forest areas in the coming decades will play an important role in reducing anthropogenic

Table 2. Carbon dioxide geologic storage resource capacity estimates for studied countries, Gt CO₂
(Filippov et al. 2022, Kök 2015, Vourliotakis et al. 2024, Kearns et al. 2017)

Country	Lower estimate			Upper estimate		
	Onshore	Offshore	Total	Onshore	Offshore	Total
Brazil	224	73	297	1572	515	2087
India	75	24	99	525	172	697
Indonesia	96	67	163	672	472	1144
Iran*	68	22	90	477	156	633
China	325	78	403	2286	544	2830
Mexico	79	59	138	556	411	967
Saudi Arabia*	89	29	119	629	206	835
Turkey*	34	11	45	238	88	326
South Africa	34		34	34	150	184

* This work estimates.

Table 3. Total capacity Q (Gt CO₂) and annual capacity G (Mt CO₂/year) of operational, in construction and under development CCS projects (according to OGCI¹⁷ and GCCSI¹⁸)

Country	Operational and in construction		Advanced development		Early development	Total
	Q	G	Q	G	Q	Q
Brazil	0,08	10.6	2.47	0,4	n/a	13
India	–	–	0.84	0,54	63.3	64
Indonesia	–	–	2.46	4,4	13.4	16
Iran	–	–	n/a		n/a	n/a
China	n/a	11.3	9.5	4	3067	3078
Mexico	n/a	–	–		138	138
Saudi Arabia	–	9.8	44		n/a	44
Turkey	–	–	–		0.1	0.1
South Africa	–	–	–		34	34

Table 4. Estimates of GHG emissions (E), LULUCF removals (S), and CCS annual capacity (G) required to achieve carbon neutrality within the expected timeframe, as well as required storage capacity by 2100 (Q_{2100}) and available geological reservoirs (Q)

Country	Year	E , Gt CO _{2eq} /year	S , Gt CO _{2eq} /year	G , Gt CO _{2eq} /year	Q_{2100} , Gt	Q , Gt
Brazil	2050	1.1	0.1	1.0	13	224
India	2070	5.5	0.2	5.3	239	75
Indonesia	2060	2.2	0.0	2.2	102	96
Iran	2080	0.9	0.0	0.9	37	68
China	2060	6.0	0.6	5.4	153	325
Mexico	2080	0.6	0.0	0.6	25	79
Saudi Arabia	2060	0.0	0.0	0.0	34	89
Turkey	2053	0.5	0.1	0.4	16	34
South Africa	2050	0.6	0.0	0.6	38	34

GHG emissions, they will not be able to completely offset increasing emissions (see Table 4).

The only solution to the carbon neutrality problem for all these countries is CCS¹⁹ technologies (Debarre et al. 2021, Cai et al. 2021, Rao et al. 2023). Although current estimates of geological rock resources for CO₂ storage (see Table 2) indicate that theoretically such storage can be found in all studied countries, the revision of operational, in-construction, and prospective CCS projects for the coming decades (see Table 3) leaves only China on this list. The lower estimates of the capacity of onshore storages from Table 2 are used as the potential volumes of geological CO₂ storages in Table 4. Simple calculations yield that after commissioning of all these huge reservoirs; Brazil alone will have nearly unlimited capacity to store the amount of GHG needed to achieve and ensure in the future its carbon neutrality. The geological reservoirs in China, Iran, Saudi Arabia, Turkey, and Mexico can store the required amounts of GHGs, but the available CCS resources in Indonesia and South Africa are clearly insufficient to meet their climate pledges, and, finally, India, with its high GHG emissions and

low CCS resources, even theoretically does not have storage capacities to meet its climate targets. In a few decades, it will be India that will take the place of China as the leading emitter of GHGs (Fig. 11) and gradually become the main obstacle to the implementation of the Paris Agreement.

To assess the scale of problems arising in the development of CCS technologies, it is worth comparing the obtained estimates of the required capacities from Table 4 with the performance indicators of modern facilities from Table 3, which differ by two orders of magnitude. This means that a new, huge industry comparable in scale to the current gas industry must be created without any delay within the next two to three decades. This new industry, which includes storage facilities, pipelines, and compressor stations¹⁹ (Cai et al. 2021, Rao et al. 2023), should have a storage capacity above 15 Gt CO_{2eq}/year by 2075. Given the current very high rates of development of the CCS industry, which average 11% per year from 2010 to 2023 (Global Status.. 2024), it is projected that a global GHG storage capacity of 10.5 Gt CO_{2eq}/year can be achieved by 2075; however, only about one-third of this capacity will

¹⁷OGCI CO₂ Storage Resource Catalogue (<https://www.ogci.com/ccus/>)

¹⁸Global Status of CCS Report 2024. Collaborating for a Net-Zero Future. Melbourne, Australia: GCCSI, 2024.

¹⁹China Carbon Dioxide Capture Utilization and Storage Annual Report. Chinese Academy of Environmental Planning / China's Ministry of Ecology and Environment, 2021.

likely be located in the studied countries, which is clearly insufficient to address the identified problems (Table 5). It should therefore be assumed that the achievement of carbon neutrality by developing countries on the whole is postponed to the end of the century, 30-40 years later than the leading OECD countries, which by that time will have to create a developed economy with negative GHG emissions to keep the global warming below 2°C.

ESTIMATION OF GLOBAL GHG EMISSIONS

To assess the global climate effect of the decarbonization measures of developing countries' economies examined in this paper, we used the results of calculations presented in our recent works for Russia (Klimenko et al. 2023a, Klimenko et al. 2024a) and economically developed countries (Klimenko et al. 2024b).

The prospects for reducing the carbon intensity of the Russian economy and the possibility of achieving carbon neutrality of the national economy by 2060 were studied in Klimenko et al. (2023a) and Klimenko et al. (2024a). Based on the historical-extrapolation approach to the study of the development of various socio-engineering systems and by comparison with the dynamics of carbon indicators of the economies of the world's leading countries, it has been demonstrated that at present the anthropogenic emissions of GHG can be compensated for by absorption by the biosphere (primarily forests) only theoretically. The condition for such an achievement is to perform extremely ambitious large-scale programs for the transformation of all sectors of the Russian economy - from the power industry to forestry management. Thus, according to the optimistic scenario, the rate of reduction of GHG emission per capita should be 1% per year, which is consistent with the maximum value achieved in the world over the past 50 years, and the forest management should include full compensation for increasing deforestation

and a 50% reduction of the forest losses caused by fires, which are currently the second (after the power industry) source of atmospheric GHG emissions. The most feasible is a scenario with 0.5%/year reduction of specific GHG emissions per capita and a moderate growth in the absorption capacity of forests mainly due to the implementation of forest climate projects and a reduction in fire emissions. Under this scenario, net GHG emissions can reach about 700 Mt CO_{2eq} by 2060, which will require the creation of a national carbon capture and storage industry that provides the large storage capacities required to achieve carbon neutrality.

The prospects for achieving carbon neutrality in economically developed countries (such as the USA, EU, Norway, Canada, Japan, and Australia) were studied elsewhere (Klimenko et al. 2024b). The structure of the power industry and land management in these countries was analyzed. Scenario estimates of the dynamics of carbon indicators of the economies of the world's leading countries have been developed. It has been demonstrated that the current rate of decarbonization and development of the CCS industry cannot ensure the achievement of carbon neutrality by 2050 even in the world's leading economies. The main challenge in achieving climate neutrality is rapid and large-scale deployment of CCS technologies capable of storing carbon for more than a century. To achieve carbon neutrality by 2050, leading OECD countries will have to store annually at least 6 billion tons of CO₂, which is almost 25 times greater than the available capacity of storage facilities (operational, in construction, and being developed).

Table 5 and Fig. 12 summarize estimates of emissions, capture by LULUCF, and CCS, as well as net GHG emissions in 2023-2100 in Russia, developed and developing countries, and the total world (Gt CO_{2eq}/year)

The pathways of CCS scale development adopted in this paper for the historical scenario correspond to the revolutionary APS8 scenario estimates for the historical

Table 5. Estimates of industrial emissions E , capture by LULUCF S , residual emissions E_{res} , CCS, and net GHG emissions (E_{net}) in 2023-2100 in Russia, developed and developing countries, and the total world (Gt CO_{2eq}/year)

Country	Scenario	2023 [*]	2050					2075					2100				
		E	E	S^*	E_{res}	CCS	E_{net}	E	S^*	E_{res}	CCS	E_{net}	E	S^*	E_{res}	CCS	E_{net}
Russia (Klimenko et al, 2023a)		2.1	1.6	1.1	0.5	0.0	0.5	1.4	1.1	0.3	0.2	0.1	0.8	1.1	-0.3	0.1	-0.4
Six developed countries (Klimenko et al, 2024b)		12.1	6.5	2.0	4.5	3.0	1.5	3.5	2.0	1.5	3.5	-2.0	2.0	1.5	0.5	3.5	-3.0
Nine developing countries**	Historical	24.1	24.3	1.5	22.8	1.0	21.8	20.1	1.5	18.6	2.5	16.1	14.8	0.8	14.0	3.5	10.5
	Intensive	24.1	22.0	3.0	19.0	2.0	17.0	13.8	3.5	10.3	4.0	6.3	8.2	3.5	4.7	4.0	0.7
Other countries**	Historical	12.2	16.8	1.5	15.3	0.5	14.8	18.4	1.0	17.4	1.3	16.1	17.4	0.6	16.8	2.5	14.3
	Intensive	12.2	15.2	3.0	12.2	1.5	10.7	12.6	1.5	11.1	2.0	9.1	9.6	2.0	7.6	3.0	4.6
Total world**	Historical	49.9	49.2	6.1	43.1	4.5	38.6	43.4	5.6	37.8	7.5	30.3	35.0	4.0	31.0	9.6	21.4
	Intensive	49.9	45.3	9.1	36.2	6.5	29.7	31.3	8.1	23.2	9.7	13.5	20.6	8.1	12.5	10.6	1.9
	IEA STEPS8	49.9	37.9			0.4											
	IEA APS8	49.9	15.5			4.5											
	BP Current Trajectory 20	49.9	36.7			0.9											
	BP Net Zero20	49.9	2.4			6.8											

* FAOSTAT scenario and GEPL1997 scenario (Klimenko et al. 2020) for historical and intensive alternatives, respectively

** this study assessment

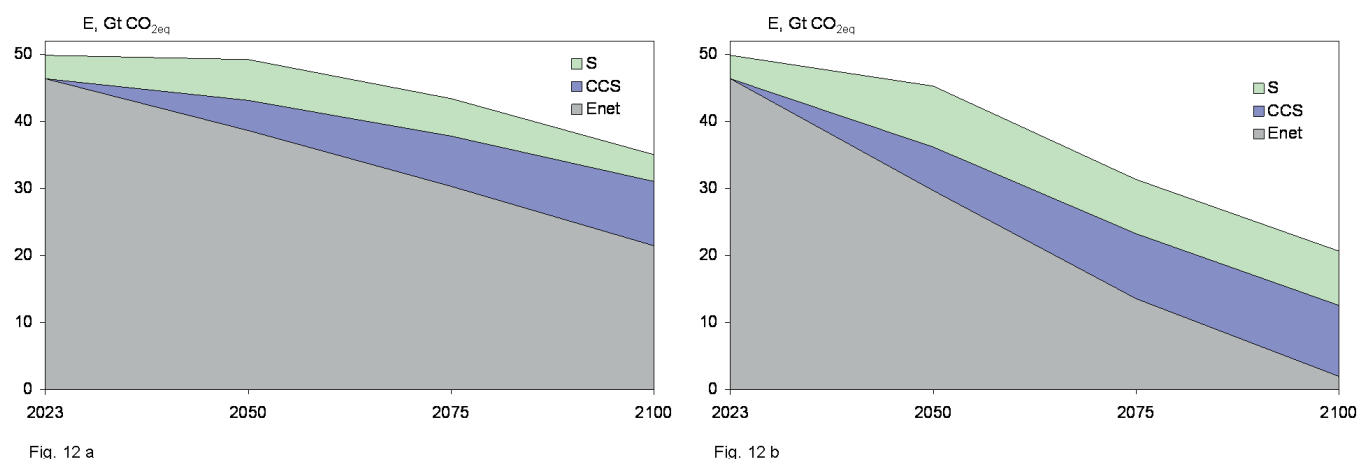


Fig. 12. Dynamics of global gross GHG emissions (excluding LULUCF) E, net sink S due to LULUCF, and carbon CCS amounts according to the calculations of this paper for the historical (a) and intensive (b) scenarios.

scenario and to the even more extreme Net Zero scenario from BP²⁰ for the intensive scenario.

The estimates of emissions in the studied countries, which were obtained in this work (Fig. 11) for the period up to 2050, are close to the STEPS scenario⁸, which assume the implementation of the current energy decarbonization policy, thereby confirming the effectiveness of the historical approach employed. The dynamics of GHG emissions under the APS scenario⁸ assume much higher rates of decarbonization of national economies, aimed at meeting the stated net zero emission targets, which are unique in history and, therefore, can hardly be attained at all.

It is also worth noting that the scenarios proposed in this paper for China, Brazil, and India are located in the range of estimates presented at the CAT portal¹⁶ (Fig. 11), which is an expert website for climate policy analysis. At the same time, attention is drawn to the CAT-provided rather high overestimates of future GHG emissions in Indonesia and Iran (Fig. 11), which are inconsistent with either current trends or expert vision⁸.

Thus, the global net GHG emissions projected by the scenarios proposed in this paper, considering the LULUCF absorption and CCS, will be 80% and 60% of the 2023 level for the historical and intensive options, respectively, by 2050, and 45% and 5% by 2100. These figures are between the “Paris” and “Glasgow” scenarios from our recent work (Klimenko et al. 2022a). The model projections (Klimenko et al. 2022a, Klimenko et al. 2022b) demonstrate that full implementation of the Glasgow scenario is able to keep the GMT within 1.5°C above the pre-industrial level, while according to the Paris scenario, it will exceed this level by 2.4°C by the end of the current century. Within the scope of the rather optimistic “intensive” scenario proposed in this paper, the temperature increase will peak at around 1.8°C, which means that the period of the dangerous temperature overshoot will be very long and likely last at least a century (Klimenko et al. 2022b).

There is no doubt that the world community’s current efforts to achieve carbon neutrality by mid-century are doomed to failure, but they are not in vain. Although the temperature increase cannot be kept below 1.5°C, we are still able to keep this parameter below the 2°C threshold and minimize residence time in the dangerous beyond-the-limit zone. According to our preliminary estimates, this beyond-the-limit period will be more than a century long, and the core problem for the global community during this period will be adaptation to previously unknown conditions and building of a global economy with negative GHG emissions. The foundations of this economy arise today.

MODEL ESTIMATES OF GLOBAL ATMOSPHERIC AND CLIMATE CHANGES

Based on the estimates of anthropogenic net GHG emissions developed in this paper, a combined climate model (Klimenko et al. 2017) along with a global carbon cycle model (Klimenko et al. 2020) were employed to simulate changes in the concentration of carbon dioxide in the atmosphere and changes in the average global temperature, and the obtained results were compared with other scenarios – “Paris” (Klimenko et al. 2016a, Klimenko et al. 2016b) and “Glasgow” (Klimenko et al. 2022a, Klimenko et al. 2022b), which assume the implementation of decisions of the relevant conferences of the UNFCCC’s parties.

The combined climate model (Klimenko et al., 2017) consists of the global energy balance model calculating the temperature response to both anthropogenic and natural forcing and a statistical block connecting the latter to the observed data. The model simulation results obtained for the last 35 years (1990–2025) are fairly consistent with the instrumental data (Klimenko et al. 2015).

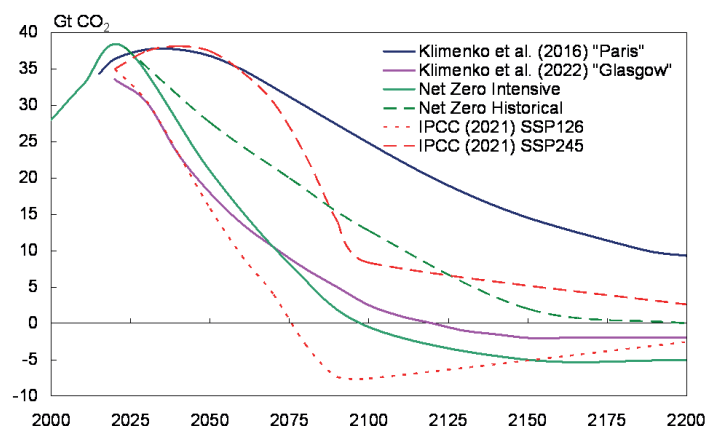
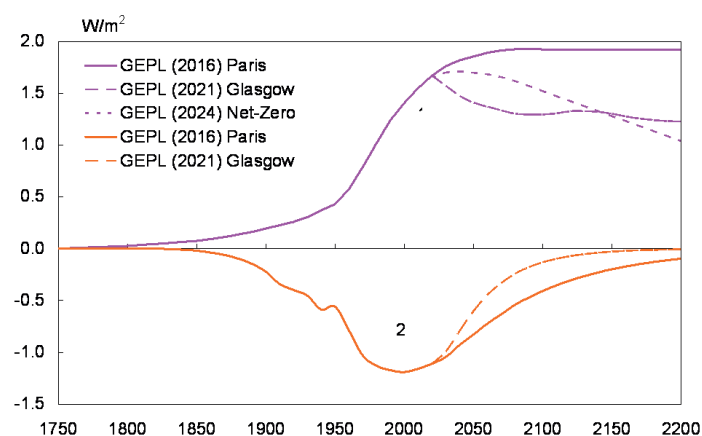
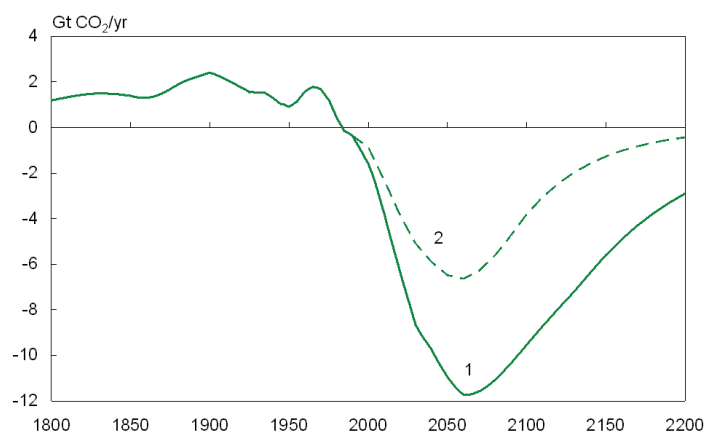
The carbon cycle model (Klimenko et al. 2020) is the global box-diffusion model with the advanced biotic block, whose projections have also shown a very good agreement with the observations of the last 25 years (Klimenko et al. 2015).

The calculations were performed using scenarios of anthropogenic industrial net emissions (emission minus storage) (indCO_2) and biotic fluxes (bioCO_2) of CO_2 , as well as radiative forcing of other GHGs (nonCO_2) and TSA of anthropogenic origin (Table 6 and Figs. 13–15). In addition, the effect of the main natural factors, such as solar and volcanic activities, as well as quasi-periodic processes in the ocean – atmosphere system, was considered.

According to the simulation results, the limits set forth in the Paris Agreement do not prevent a further temperature increase of up to 2.4°C by the end of the 21st century and nearly 3°C by the end of the 22nd century and are completely insufficient. At the same time, as we have already pointed out earlier in (Klimenko et al. 2023b), even the sluggish Paris limitations are not fully implemented today. Regarding the limits outlined in the Glasgow Pact, only their full and timely implementation will allow for keeping global warming below the targeted 1.5°C. However, an analysis of current trends shows that the Glasgow scenario rather demonstrates such a possibility, but in fact it cannot be implemented since the existing developing historical trends (Klimenko et al. 2023b, Klimenko et al. 2024c) cannot be overcome. At present, deployment of the most revolutionary scenario, NetZero Intensive, still

Table 6. Combinations of scenarios of emissions and anthropogenic forcings for selected scenarios

Scenarios	Emission		Forcings	
	ind.CO ₂ with CCS	bioCO ₂	nonCO ₂	TSA
«Paris»	«Paris» (Klimenko et al. 2016a, Klimenko et al. 2016b)	FAOSTAT (Klimenko et al. 2020)	«Paris» (Klimenko et al. 2016a, Klimenko et al. 2016b)	«Paris» (Klimenko et al. 2016a, Klimenko et al. 2016b)
«Glasgow»	«Glasgow» (Klimenko et al. 2022a, Klimenko et al. 2022b)	GEPL'97 (Klimenko et al. 2020)	«Glasgow» (Klimenko et al. 2022a, Klimenko et al. 2022b)	«Glasgow» (Klimenko et al. 2022a, Klimenko et al. 2022b)
Net-Zero Intensive	This work	GEPL'97 (Klimenko et al. 2020)	This work	«Glasgow» (Klimenko et al. 2022a, Klimenko et al. 2022b)
Net-Zero Historical	This work	FAOSTAT (Klimenko et al. 2020)	This work	«Glasgow» (Klimenko et al. 2022a, Klimenko et al. 2022b)

**Fig. 13. Dynamics of industrial net-emissions of carbon dioxide (considering CCS) – history⁷, scenarios SSP126 and SSP245 (Gidden et al. 2019, Meinshausen et al. 2019), and from this work (Table 6)****Fig. 14. Dynamics of radiative forcing of other GHGs (1) and tropospheric sulfate aerosol (2) – history (IPCC 2021) and scenarios from Table 6****Fig. 15. Dynamics of biotic carbon fluxes (from LULUCF with bioproductivity change): history (IPCC 2021) and scenarios (Klimenko et al 2020) GEPL1997 (1) and FAOSTAT (2)**

Results of GMT simulations are presented in Fig. 16.

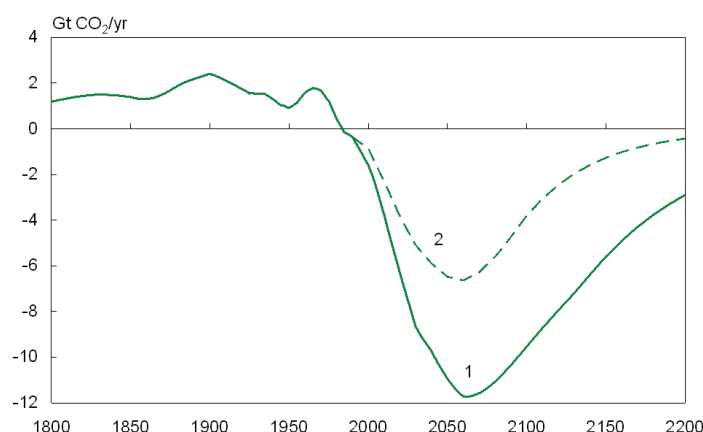


Fig. 16. Dynamics of the GMT (referenced to the average over 1850-1900) – history (CRU¹), model simulations according to scenarios in Table 6 and (IPCC 2021; Klimenko et al. 2016; Klimenko et al. 2022b) studies.

seems feasible. It envisages that the temperature increase will reach its maximum of about 1.8°C at the end of this century and then gradually decline to the current values as a result of removing excess CO₂ from the atmosphere. However, even with this most revolutionary scenario, the period of the dangerous temperature overshoot above 1.5°C will likely last longer than a century.

RESULTS AND DISCUSSION

Figs. 11 and 13 compare the estimates of production and net emissions of greenhouse gases predicted in this work with the results of other studies carried out by leading global energy agencies (IEA⁸, BP¹⁹), as well as academic institutions within the scope of the IPCC activities (Gidden et al. 2019, Meinshausen et al. 2019)²⁰. Since the time horizon of energy forecasts of IEA8, BP19 is limited to 2050, for closer comparison, this time interval is shown in Fig. 17.

Despite the fundamental difference in the approaches to the simulation of the development of the power industry and other fields of human activities, the scenarios of application of the decisions of the UNFCCC parties conferences in Paris (2015) and Glasgow (2021), developed earlier by the authors of this paper, agree well with the low SSP245 and SSP126 scenarios (Gidden et al. 2019, Meinshausen et al. 2019), respectively.

As for the estimates of the present work, in the period up to 2050 they lie in a much narrower range, approximately halfway between the SSP245 and SSP126 trajectories. The “NetZero Historical” scenario is consistent with the inertial forecasts STEPS⁸ and Current Trajectory²⁰ of the energy agencies, which indicates a proper interpretation of the current trends in the global energy and the overall global economy within the scope of this work. Considerable differences are observed when comparing more radical scenarios. The accelerated decarbonization pathways of the APS⁸ and Net Zero²⁰ scenarios assume exceptionally high rates of net GHG emissions decrease, reducing them by several times (by three times for APS scenario and by more than 10 times for Net Zero scenario) in just two and a half decades. In such an inertial system as the energy industry, such rates of radical change can hardly be attained at all.

Calculations of the cumulative (2020-2200) biotic carbon uptake according to the projections of the present

study (160 Gt C for the historical scenario and 330 Gt C for the intensive one) are fairly consistent with its current potential estimates from Mo et al., 2023: 150-350 Gt C.

Over a longer time period (up to the end of the current century and further – see Fig. 9), the net GHG emissions scenarios proposed in this paper follow the trajectories of long-term SSP scenarios. The emission according to the NetZero Historical scenario by 2100 in its cumulative value roughly agrees with the SSP2-45 estimates, and according to the NetZero Intensive scenario, just like in the SSP1-26 option, it goes into the negative area, but only 20 years later.

The results of model simulations of changes in the GMT, performed using the authors’ complex of models of the global climate system and presented in Fig. 12, are in good agreement with the IPCC estimates (IPCC 2021) obtained within the scope of the project of comparing the results of CMIP6 climate models for the corresponding scenarios. Thus, a growth in the GMT according to the “Paris” scenario agrees with the SSP2-45 model calculations, according to which the GMT will increase compared to the preindustrial level by 2°C by 2050 and by 2.7°C by 2100. The results of calculations for the NetZero Intensive scenario are close to the estimates of the SSP1-26 option, according to which the GMT peaks at 1.7-1.8°C above pre-industrial level in the second half of the current century.

Thus, employing here the historical-extrapolation approach to the projection of the development of the energy sector and other fields of business activities and their impact on the global climate system yields results that are quite consistent with the outcome provided by other methods of simulation of socio-engineering systems. Our findings show that the historical approach can probably more accurately capture the boundaries of potential future changes, which makes it a valuable tool in constructing long-term adaptation scenarios.

CONCLUSIONS

1. All studied countries are considerably behind schedule in their emissions reduction activities, and none of them is on track to achieve carbon neutrality within the specified timeframe.

2. In various relevant areas of human activities characterized by considerable inertia (power industry, agriculture and forestry, other industries), certain historical

²⁰By the issue of the IPCC Sixth Assessment Report (IPCC 2021), a group of scenarios of anthropogenic impact on the atmosphere and climate, SSP (“Shared Socioeconomic Pathways”), was developed, offering various trajectories of greenhouse gas emission dynamics depending on the target level of impact by 2100 and the paths of global socio-economic development. This paper intentionally ignores the most severe of them – SSP3-7.0 and SSP5-8.5, which assume that anthropogenic emissions will not only retain their current level but even will grow at a higher rate, as well as the unjustifiably optimistic SSP1-1.9, aimed at achieving the climate neutrality by 2050.

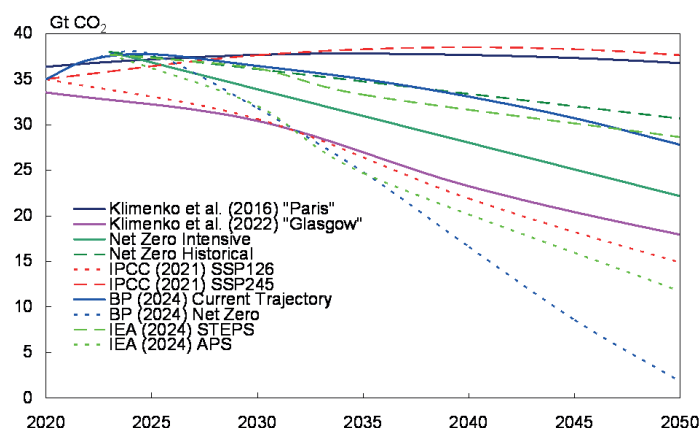


Fig. 17. Scenarios of industrial net emission of carbon dioxide (considering CCS): SSP126 and SSP245 (Gidden et al. 2019, Meinshausen et al. 2019), STEPS and APS of IEA⁸, Current Trajectory and Net Zero of BP²⁰, and this work (Table 2)

patterns have profound effects that prevent the desired transformations from being carried out at arbitrary rates.

3. The climate protection targets set by the studied countries cannot be attained since the capacities available in these countries are not adequate to transform their economies even in the face of increasing climate risk.

4. The window of opportunity has closed finally. The

threshold of conditionally safe warming of 1.5°C will inevitably be exceeded in the next ten years, and the period of the dangerous temperature overshoot will be longer than a century.

5. The focus of the global community's efforts should be gradually shifted from mitigation to adaptation to unique climate conditions based on proactive measures. ■

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THE LATE HOLOCENE CLIMATIC EVENTS ON THE SOUTHERNMOST RUSSIAN FAR EAST COAST: VARIABILITY DRIVERS

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ABSTRACT. Hydroclimatic changes along the southernmost coast of the Russian Far East, as reconstructed over the past 2460 years, were primarily driven by the intensity of monsoon circulation that was strongly influenced by solar activity and processes in the low-latitude Pacific. An analysis of ecological indicators of Lotus Lake environment (diatoms, botanical composition, mineral content) revealed periods of increased and decreased lake level that corresponded to strengthening and weakening of the summer monsoon. Lotus Lake experienced six stages of increasing and decreasing of lake watering. The basin originated as a meso-eutrophic lake connected to the sea. The connection between the lake and the sea was interrupted ~2100 yr BP, which caused a change in the geochemical environment. To understand hydroclimate changes, data on surface temperature anomalies in the western tropical Pacific Ocean were used. These anomalies were strongly influenced by El Niño. Changes in the intensity of the warm Kuroshio Current were one of the factors that influenced precipitation. A comparison of regional data showed spatial heterogeneity in the moisture distribution, which was associated with changes in typhoon tracks during the Late Holocene. The paleoclimatic situation on the southernmost coast of the Russian Far East, which experienced a relatively dry Medieval Climate Anomaly and a wet Little Ice Age, was similar to that of Korea. A sharp decrease in lake depth and swamping of the shores occurred at two periods: at the beginning of global cooling (1650–1600 yr BP), and 1230 yr BP, when there was a slight cooling trend and El Niño activation. The greatest variability in environments occurred during the last millennium. There were frequent and abrupt climatic variations, particularly during the Little Ice Age. Evidence of temperature and hydrological changes was obtained for the solar minima; the swamp wetness around Lotus Lake decreased.

KEYWORDS: coastal lake, hydroclimatic changes, monsoon, typhoon tracks, ENSO, Kuroshio Current

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INTRODUCTION

Lakes located on the coast are sensitive archives of short-term climate changes. Shallow lakes are of particular interest for reconstructing hydroclimatic changes because they are sensitive to changes in precipitation associated with the summer monsoon intensity in the southern Far East (Li et al. 2011; Park et al. 2017; 2023). The analysis of the alternation of watering and swamping phases in the development of such lakes (Razjigaeva et al., 2025a) is useful for high-resolution reconstructions of ecosystem dynamics. Due to continuous sedimentation and high sedimentation rates, coastal lake archives can be used to analyze mechanisms of paleoclimatic shifts at the continental margin and reconstruct atmospheric

circulation anomalies. These anomalies were determined by changes in the intensity and position of atmospheric centers and the influence of processes that occurred in the low-latitude Pacific (Woodruff et al., 2009; Hu et al., 2016). Studying the long-term dynamics of coastal lakes provides valuable information on their possible future development, which is important in terms of bioresources and land use. In recent years, a series of reconstructions using modern approaches have been performed on coastal lakes in Primorye (Lozhkin et al., 2021; Nazarova et al., 2021; Lyashchevskaya et al., 2023; Razjigaeva et al., 2020, 2023, 2024, 2025a). Logically, this requires obtaining data on the evolution of lakes in southern Primorye, near the boundary of the temperate zone and subtropics. This work aims to reconstruct hydroclimatic

changes caused by variations in summer monsoon intensity and cyclogenesis activity based on the analysis of Lotus Lake’s development over the last 2500 yr.

REGIONAL SETTING

Lotus Lake (2.9 × 1.8 km) is located 9 km from the seashore on an alluvial-marine plain. It is situated 2.5 km from the Tumannaya (Tumangan) River. The lake had a barrier origin and formed in a shallow depression surrounded by highlands (up to 90 m) in the late Holocene (Mikishin et al., 2008). The lake’s depth reaches 2 m, and small streams flow into its northern part. Along the western and northern shores, there is a swamp up to 90 m wide.

The climate is monsoonal. The mean annual temperature is 5.9°C, the January mean is -10.3°C and the August mean is 21°C; the absolute maximum was 36.4°C, and the minimum was -27.2°C. The mean annual precipitation is 704 mm. The most rain falls in August (up to 162 mm), and the least falls in January (8 mm). The prevailing wind direction throughout the year is westerly (38%)¹. Lotus (*Nelumbo nucifera*) grows abundantly in the lake. The upland areas are covered with stunted oak forests and shrub thickets. Reedgrass (*Phragmites australis*), sedges (*Carex lasiocarpa*, *C. cryptocarpa*, *C. pseudocuraica*) and various grass meadows and swamps occupy the accumulative plain.

MATERIALS AND METHODS

A hand-bored hole was drilled using a Russian peat borer Instorfa in the western part of the lake (42°27.470’N; 130°38.203’E), at the contact between the swamp and the floating bog (Fig. 1). Light gray, fine silty sand was uncovered at the base of the section (235–230 cm). Above

that (230–115 cm), dark brown gyttja (organic-rich silt) with a sedge peat layer (150–155 cm) was found. The upper part (0–115 cm) consists of dark brown, moderately decomposed sedge-hypnum (85–115 cm) and sedge peat (0–85 cm). We sampled continuously at 5-cm intervals. Diatom and botanical analyses were performed according to standard methods. The concentration of diatom valves in 1 g of air-dry sediment was calculated. For ecological characteristics of individual species, we used (Krammer, Lange-Bertalot, 1991; Kharitonov, 2010; van Dam et al., 1994). We studied the botanical composition of the sediments using the manual of Kulikova (1974) and recorded the presence of macrocharcoal fragments. Quantitative estimates of macrocharcoal content (by volume) were recorded where it constituted >5% of the analyzed material using a microscope. The peat was tested for mineral content (i.e. non-organic content) after ignition at 550 °C. Selected samples were radiocarbon dated in the Institute of Earth Sciences, St. Petersburg State University (Table 1). Radiocarbon dates were calibrated using OxCal v.4.4.1 and the IntCal 20 calibration curve (Reimer et al., 2020). The age-depth model was constructed using the Bacon 2.2 program (Blaauw and Christen, 2011). Scanning electron microscopy and X-ray microanalysis of volcanic glass shards were performed at the V.G. Khlopin Radium Institute, St. Petersburg.

RESULTS

Age model, sedimentation rates, mineral content, tephra

According to the age-depth model (Fig. 2), the accumulation of gyttja began ~2410 yr BP. A thin layer of sedge peat formed 1650–1600 yr BP. Sedge-hypnum peat began to form at 1230 yr BP, and sedge peat – since 860 yr

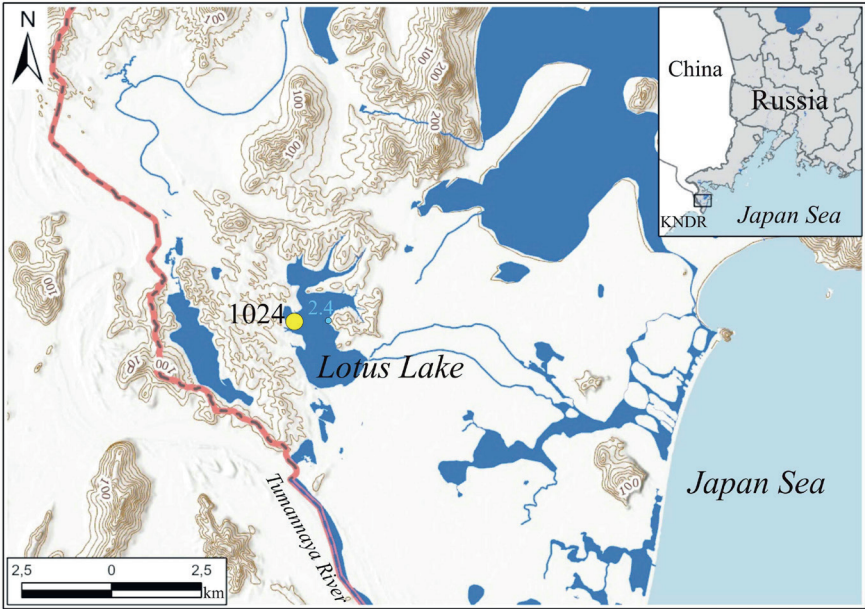


Fig. 1. Study area

Table 1. Radiocarbon and calendar ages of lacustrine-swamp sediments (sections 1024) on the coast of Lotus Lake

Sample N	Depth, m	Material	¹⁴ C age	Calendar age, cal yr BP (2σ)	Lab. N LU-
9/824	0.40–0.45	peat	382 ± 81	410 ± 82	11671
18/824	0.75–0.80	peat	808 ± 119	760 ± 100	11674
26/824	1.20–1.25	gyttja	1605 ± 178	1530 ± 180	11670
40/824	1.90–1.95	gyttja	2094 ± 157.5	2070 ± 200	11673

¹<https://www.primgidromet.ru>

BP. Sedimentation rates were uniform at 0.8–1 mm/yr. The temporal resolution of the reconstructions is 46–60 years.

The sequence includes cryptotephra, represented by high-potassium volcanic glass, the source of which was the Baitoushan volcano. In the lower part of the section, the age of the peat with cryptotephra is 2060–2010 yr BP. An eruption of this age is known from the Erdaobaikhe Museum, China. Cryptotephra B-Tm of the caldera-forming eruption (946/947 CE) with terrigenous material was found too. In the upper part, cryptotephra found at 0.40–0.45 cm has an age of 410–350 yr BP, which is close to the eruption of 1597 CE.

Gyttja from the lower part of the section (2460–2100 yr BP) has the highest mineral content (80–87%). Above that, the mineral content decreases (58–68%). The mineral admixture decreased sharply 1170–860 yr BP. In the overlying peat, the mineral content increased and varied sharply. The maximum was noted in peat formed 690–630 yr BP and 470–410 yr BP; the minimum was noted 240–110 yr BP.

Diatom analysis

In total, 247 taxa of freshwater diatoms were identified in the sediments. Epiphytes dominate (125 species), benthic species – 112 and planktonic and temperate planktonic species – 10. There were also ten marine sublittoral species. The diatom distribution suggests 6 stages in lake evolution (Fig. 3).

The first stage occurs between 2460 and 2100 years BP. The presence of freshwater and marine sublittoral species (up to 1.2%) reflects the development of a meso-eutrophic lake connected to the sea. Among freshwater diatoms, epiphytes dominate: *Staurosira venter*, *S. construens*, *Pseudostaurosira elliptica*, and *P. brevistriata* prevail. These species develop in oligotrophic to eutrophic, stagnant waters (van Dam et al., 1994; Krammer and Lange-Bertalot, 1991). Among plankton, *A. granulata* and *A. ambigua*, typical for eutrophic lakes, are the most frequent. High valve concentrations indicate favorable conditions for diatom development. Coastal marine diatoms are represented by the benthic species and planktonic *Paralia sulcata*.

Stage 2 occurs between 2100–1600 yr BP. The role of *Staurosira construens* significant decreases. Perhaps the limiting factor was the increase in nitrogen concentrations caused by the lake's overgrowth. *S. venter*, tolerant of high nitrogen concentrations (van Dam et al., 1994), developed more extensively. A change in the pH may have also played a role due to reduced marine influence for groundwater under a regression (Korotkii et al., 1997). Single valves of the sublittoral *Diploneis pseudovalis* and *D. interrupta* entered the lake during strong storms. The peat layer includes the highest content of the genera *Eunotia* and *Pinnularia*, typical for swamps.

Stage 3, spanning from 1600–1230 yr BP, was observed. The abundance of *Staurosira binodis*, which inhabits meso-eutrophic lakes, increases in the upper part, reflecting more intensive overgrowth of the lake. *Eunotia monodon* var. *tropica*, which inhabits the tropical and subtropical lakes, appeared.

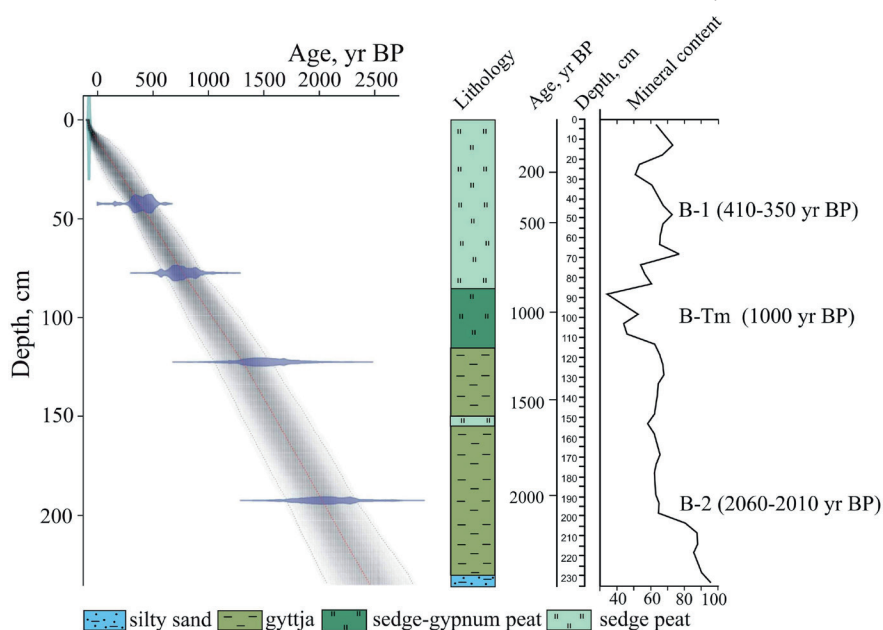


Fig. 2. Age-depth model, lithology, and mineral contents for Lotus Lake sediments; ^{14}C dates with standard deviations are shown in blue; the gray curve shows the 95% confidence interval

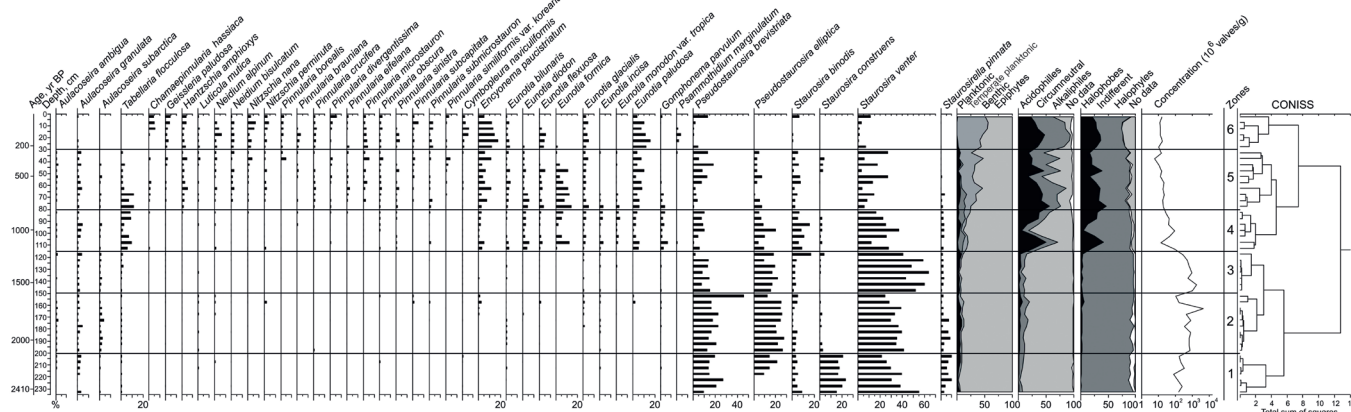


Fig. 3. Diatom percentage diagram for Lotus Lake sediments

Marine species were brought in by strong storms 1500–1400 yr BP.

Stage 4, spanning from 1230 to 800 years BP, has been identified. Diatoms reflect a reduction in lake area. The shores became waterlogged and overgrown. The lake level changed frequently, resulting in unstable ecological conditions. Temporarily planktonic acidophilic *Tabellaria flocculosa*, which preferred shallow lakes and peat bogs (Krammer and Lange-Bertalot, 1991), became dominant. The content of halophobes and acidophiles, represented mainly by the genus *Eunotia*, increases significantly. The content of cold-water cosmopolites increased. *Eunotia monodon* var. *tropica* indicates that the lake is well warmed in summer.

Stage 5 occurs between 800–240 yr BP. Diatoms reflect an unstable regime. The proportion of benthic species, mainly from the *Pinnularia* genus, increases up to 44%. Aerophytic *Chamaepinnularia hassiaca*, typical to peatlands, appeared. The participation of *Eunotia paludosa* is also more pronounced. Lower concentrations could be related to a decrease in moisture 350–300 yr BP. This observation is confirmed by the high content of soil diatoms.

Stage 6 covers the last 240 years. The presence of *Geissleria paludosa*, tolerant to temporary drying, *Pinnularia borealis*, and *Hantzschia amphioxys*, typical for soils, indicates soil processes development during dry seasons. Abundant species tolerant of temporary drying, such as *Encyonema paucistriatum* and *Eunotia paludosa*, increased. Significant quantities of *Staurosira venter*, *Pseudostaurosira brevistriata*, and *S. binodis* in the turf indicate flooding of the swamp during strong typhoons in recent years.

Botanical composition

Eight zones have been identified, demonstrating the development of vegetation from shallow lake to fen (Fig. 4).

Zone 1 dates back to 2460–1960 yr BP. Remains of aquatic plants, including *Potamogeton gramineus*, which grows at depths up to 1 m, prevail. The amount of plant remains increased in the gyttja formed after 2200 yr BP. The upper part contains *Brasenia schreberi* and seeds of *Najas* and *Nelumbo nucifera*. Terrestrial plant remains include burnet (*Sanguisorba*), green mosses, sedges, and reeds. Green algae, cladocera, and charcoal are present.

Zone 2 was established between 1960–1800 yr BP. The lake shores began to overgrow with club rush (*Schoenoplectus tabernaemontani*) and sedges. Cotton grass and Potentilla pentandra appeared on the swampy shores. The hydrophyte *Myriophyllum spicatum*, which inhabits standing and slow-flowing waters, appeared. Colonies of bryozoans (*Plumatella*) became widespread on the lake bottom.

Zone 3 occurred between 1800–1230 yr BP. Overgrowth of the shores increased. The decrease in pondweed and the increase in sedge proportions reflect a trend of decreasing lake

depth 1800–1650 yr BP. The presence of *Sphagnum* indicates cooling 1700–1650 yr BP. Fires occurred in 1750–1710 yr BP and continuously 1450–1230 yr BP.

Zone 4 occurred between 1230 and 860 years BP. A watered hypnum-sedge fen was formed. *Drepanocladus aduncus* was common. Moss (*Climacium dendroides*) grew in the initial stage. Herbaceous plants included sedges, *Rhynchospora*, typical for floating bog, *Phragmites*, *Lobelia sessilifolia*, *Equisetum*, *Iris*, *Calamagrostis*, and the fern *Thelypteris*. Water plants remains (*Brasenia schreberi*, *Nelumbo nucifera*) were found. Reed mace (*Typha*) and club rush (*Schoenoplectus tabernaemontani*) grew near the shore. The soil testate amoeba (*Cyclopyxis kahli*) may have been transported from the slopes.

Zone 5 occurred between 860–410 yr BP. A sedge swamp developed. The role of *Calamagrostis langsdorffii* decreased sharply after 690 yr BP under wetter conditions. Remains of aquatic *Nuphar pumilum* are present. Finds of *Glomus* show that there was disturbed land nearby. Conifer wood may have been brought by flooding. The presence of blueberry (*Vaccinium*) and a peak of *Calamagrostis* indicate a decrease in wet conditions between 520 and 470 yr BP. Intense fires occurred 740–690 yr BP.

Zone 6 occurred between 410–240 yr BP. There was still a floating bog with overgrown sedges. The abundance of *Carex appendiculata* that formed large bumps indicates significant fluctuations in the lake level. Green mosses developed only up to 350 yr BP under wetter conditions. Birch bark appeared. *Glomus* was also found. Fires occurred regularly.

Zone 7 spans from 240 yr BP to the mid-20th century. The reed-sedge bog became less wet. Intense fires occurred at the beginning and end of this phase.

Zone 8. In the last few decades, liverworts were found sporadically; favorable conditions for their development probably occurred after floods or during frequent visits by people to the shore, where an observation tower was built.

DISCUSSION

Lake Evolution at the Late Holocene

According to the age-depth model, Lotus Lake formed approximately 2460 yr ago, which confirms the data obtained earlier (Mikishin et al., 2008). The lake was formed within a catchment area separated by a barrier. During the middle Holocene, this area was part of a marine bay (Mikishin et al., 2024). The further development of the shallow lake was closely related to hydroclimatic changes. The development of an accumulative plain at the mouth of the Tumangan River also influenced the lake's evolution. The river's stream migrated southward due to active accumulation of loose material supplied by the river and transported southward.

In the initial stage, fine sand was deposited in the marginal part of the lake, and sedimentation of gyttja began at 2407 yr BP. The high-resolution record obtained makes it possible to

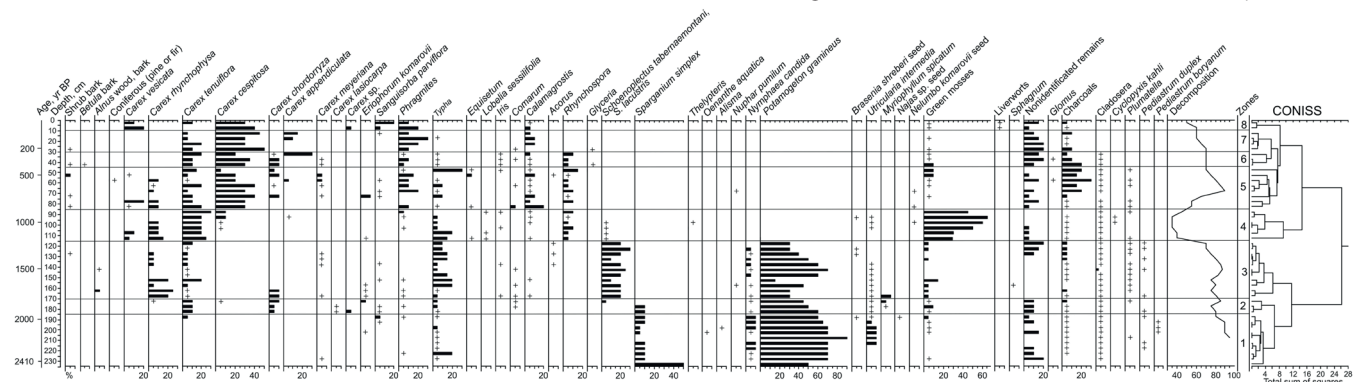


Fig. 4. Botanical composition of Lotus Lake sediments plus records of some microfauna, charcoal, terrigenous input, and tephra

reconstruct the lake's evolution in detail.

The sequence records the transition from global cooling to warmer conditions comparable to the Roman warming period (Fig. 5k). This warming was insignificant and caused no major ecological changes to the ecosystem. The initial stage of lake development occurred during a period of slight increases in precipitation. Flooding 2430–1770 yr BP was also recorded in the development of peat bogs on the Boisman Bay coast (Razjigaeva et al., 2025a). The progradation of the seashore and subsequent disconnection of the lake from the sea during minor regression (Korotkii et al., 1997) led to a change in geochemical environments and a shift in the dominant diatoms ~2100 yr BP. These changes created more favorable conditions for diatom development, and valve concentrations in sediments increased significantly (up to 4698×10^6 valves/g). During this period, the terrigenous influx into the lake decreased. Since the main source of mineral admixture was hollow waters, we conclude that precipitation likely decreased as well, resulting in drier conditions. Shallowing of Gniloye Lake on the Nakhodka Bay coast (Lyashchevsky et al., 2023) and the paleolake at the top of the Amur Bay (Razjigaeva et al., 2023) were noted ~2010–2000

yr BP too. The periphery of Lotus Lake was actively overgrown with *Potamogeton gramineus*, one of the main sources of organic material. During the warming period (2060–1960 yr BP) *Brasenia schreberi* and *Nelumbo nucifera* appeared among the aquatic plants. The appearance of *Myriophyllum* indicated a stagnant regime 1800–1750 yr BP.

During the cooler and drier climate of 1750–1710 yr BP, the swampy shore became overgrown with alder, and fires became more active. These fires were likely associated with human development of the coast (Kuzmin et al., 2005). The beginning of cooling ~1740 yr BP was recorded on the Amur Bay coast (Razjigaeva et al., 2023). Along the southern coast of Primorye, this period was characterized by decreased precipitation (Mikishin et al., 2008).

At the beginning of the cooling period (1700–1650 yr BP), Lotus Lake became slightly shallower. Sedges appeared along the shoreline, and a brief sedge swamp developed (1650–1600 yr BP). Diatom concentrations dropped sharply (Fig. 5a). The dry period associated with the cooling at 1650 yr BP was also evident on the Nakhodka Bay coast (Lyashchevskaya et al., 2023).

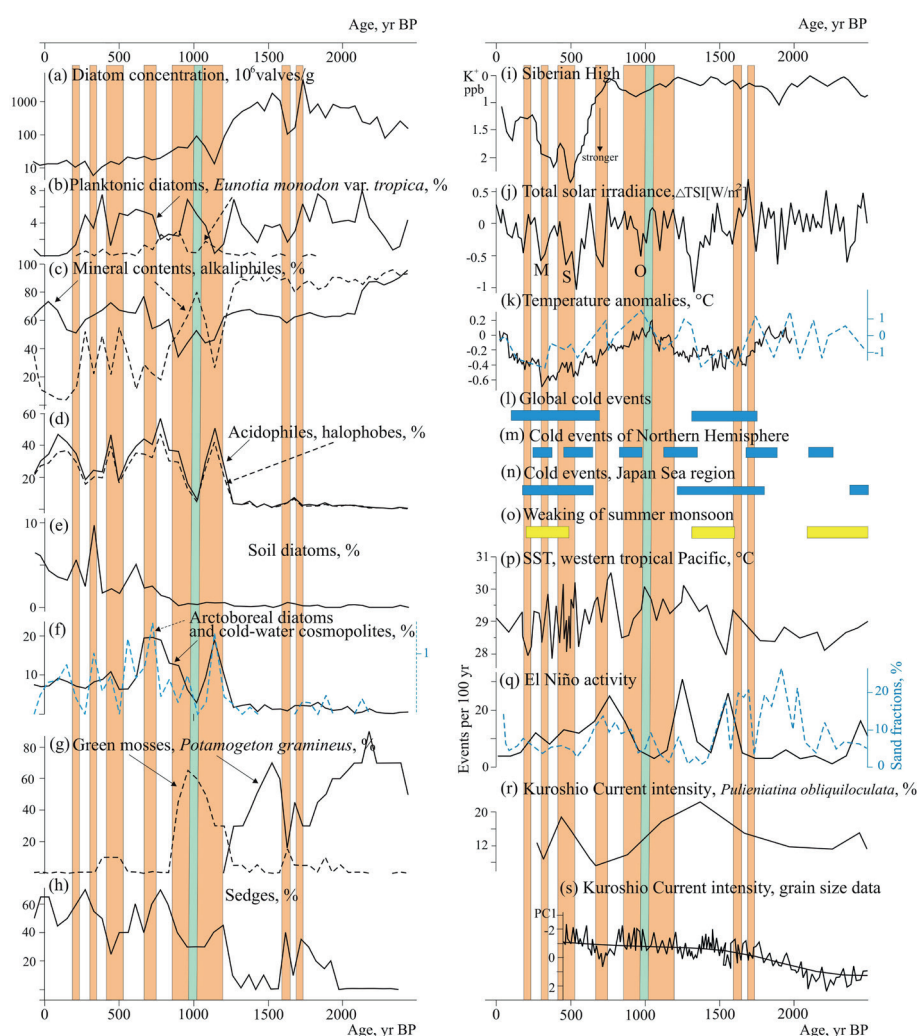


Fig. 5. Synthesis of data on the biotic component reconstruction compared to paleoclimatic proxy. (a–h) biotic components of Lotus Lake; (i) K⁺ concentration in the Greenland GISP2 ice core, a proxy for the intensity of the Siberian High (Mayewski et al., 2004); (j) TSI variability based on ¹⁰Be measurements in polar ice (Steinilber et al., 2009), Grand Solar Minima: M – Maunder, S – Spörer, O – Oort; (k) black line – Decadal mean air temperature variations (°C) relative 1961–1990 CE, Northern Hemisphere (90–30°N) (Ljungqvist, 2010); blue line – deviation of annual temperatures for Amur River Region from modern average temperature (Klimenko et al., 2000); (l) global cold events (Wanner et al., 2011); (m) cold events, Northern Hemisphere, (Gorbarenko et al., 2024); (n) cold events, Japan (Sakaguchi, 1983); (o) weakening of summer monsoon (Chen et al., 2015; Li et al., 2011); (p) SST variations, western tropical Pacific (Stott et al., 2004); (q) black line – El Niño events per 100 years (Moy et al., 2002), blue line – content of sand in the sediments of Junko Lake, Galapagos (Conroy et al., 2008); (r, s) abundance of the warm water species *Pulleniatina obliquiloculata* (Jian et al., 2000) and grain-size data (Ding et al., 2022), as proxy of Kuroshio Current intensity: vertical bars show yellow – dry periods, and blue – wet periods

Slight flooding of Lotus Lake occurred due to an increase in river inflow 1600–1230 yr BP. The shores began to overgrow with *Scirpus* and *Typha*, while pondweed continued to dominate among aquatic plants near the shore. The presence of the *Eunotia monodon* var. *tropica* in the lake indicates that the water warmed up considerably in the summer. Conditions in the southernmost Primorye were much warmer than those in Peter the Great Bay, where cooling persisted until 1300 yr BP (Lyashchevskaya et al., 2023). The increase in fire frequency and intensity 1450–1230 yr BP can probably be attributed to human development along the coast (appearance of Mohe settlements). Storm activity, as indicated by the presence of marine diatoms, increased 1500–1400 yr BP, which is consistent with the Boisman Bay data, where strong storms were recorded 1650–1440 yr BP.

The most contrasting changes in Lotus Lake's development occurred at 1230 yr BP, when the shores began to swamp due to decreased atmospheric precipitation. The concentration of planktonic diatoms decreased significantly (Fig. 5b). Hypnum-sedge peat began to accumulate. At the same time (1240 yr BP), the paleolake on Shkot Island began to be actively swamped (Razjigaeva et al., 2020).

A slight cooling in the sediments of Lotus Lake was recorded 1170–1100 yr BP by an increase in the content of cold-water cosmopolites and arctoboreal diatoms (Fig. 5f). Diatom concentrations fell sharply. During the Medieval Climate Anomaly, sedge-hypnum peat began to accumulate near the lake shores (from 1100 yr BP). The sharp decrease in mineral content (Fig. 5c) indicates that at this time the terrigenous input with river runoff and slope wash was decreasing. The amount of precipitation in the southernmost Primorye decreased. Increased effective evaporation under warmer conditions than the present day apparently also played a role in the development of the bog. A small cold signal – an increase in the content of arctoboreal diatoms and a decline in *Eunotia monodon* var. *tropica* (Fig. 5b, f) – is juxtaposed with the Oort solar minima (Fig. 5j). The minimum mineral content was observed at ~920–860 yr BP, the number of planktonic diatoms decreased (Fig. 5b), and the participation of *Drepanocladus aduncus* sharply increased on the peatland.

Dry phases of close age were also recorded in other peatlands. On the Amur Bay coast, a sharp decrease in the paleolake level was recorded at ~1190–970 yr BP (Razjigaeva et al., 2023). A decrease in peatland flooding at the paleolake site was also recorded in the Boisman Bay. To the north on the Primorye coast, the situation was different. On the Nakhodka Bay coast, the second half of the Medieval Climate Anomaly (1060–840 yr BP) was humid (Lyashchevskaya et al., 2023), while in Eastern Primorye, an increase in humidification was observed since 1300 yr BP (Razjigaeva et al., 2025b).

The swamp along Lotus Lake became a sedge swamp 860 yr BP. As the development of clump-forming sedges progressed, the amount of reed grass (*Calamagrostis langsdorffii*) increased. The moisture regime changed from constant to variable, contrasting by seasons. A sharp increase in mineral content in peat (Fig. 5c) indicates strong floods caused by strong typhoons. The degree of peat decomposition increased which was also affected by regular fires.

During the Little Ice Age (LIA), Lotus Lake had an unstable hydrological regime, which was also typical for other coastal lake development in Southern Primorye (Razjigaeva et al., 2024, 2025a). On the one hand, there was an increase in watering of the swamp along the lake, and

on the other hand, there were drier periods, as evidenced by the decrease in mineral content 800–690 yr BP and the development of soil diatoms (Fig. 5c, e). Their peaks, along with arctoboreal species, record a cold and dry event 350–300 yr BP, which was close to the Maunder minima (Wanner et al., 2022). The signals to the Spörer minima were recorded by an increase in cold-water cosmopolites, acidophiles, and halophobes (Fig. 5d, j), indicating active swamp waterlogging. At 690–350 yr BP the development of swamp vegetation was strongly influenced by the pyrogenic factor; fires were most likely of anthropogenic nature. Finds of the *Glomus* complex indicate the proximity of disturbed lands. In general, the first half of the LIA (up to 520 yr BP) was colder. Lotus Lake framing swamp became less wet 240 yr BP, which was well observed in the development of other peatlands (Razjigaeva et al., 2024; 2025a). The mineral content decrease of peat corresponds to a decrease in mineral input to the lake 240–110 yr BP. Higher content of cold-water cosmopolites was observed in peat that accumulated in the late 18th–early 19th centuries (Dalton minimum). Since the middle of the XIX century, the swamp developed in unstable conditions – with high watering and increased frequency of floods in recent decades, there are signs of anthropogenic influence (Busse, 1898).

Short-time climatic events, correlation and main drivers

A detailed record of changes in biotic components recorded in Lotus Lake sediments allows us to characterize hydroclimatic events on the multi-decadal scale (see Fig. 5). Changes in moisture in the region were primarily related to variations in the summer monsoon, which controlled the main mass of atmospheric precipitation. The investigations for central and northeastern China and the Korean Peninsula show that summer monsoon intensity and precipitation anomalies on decadal to centennial scales were strongly dependent on variations in solar irradiance, which determined the contrast between the tropical Pacific and the Asian continent (He et al., 2013; Chen et al., 2015; Park et al., 2017).

The investigations on modern climate variability show that processes within ocean-atmosphere zone interaction at low latitudes in the western Pacific Ocean, including variations in the SST and El Niño, play an important role in altering the monsoon circulation (Byshev et al., 2014; Kwon et al., 2010; Hu et al., 2015; Xu et al., 2016). An important component of the climate system is the warm Kuroshio Current, the low-frequency variability of which plays a major role in the distribution and meridional exchange of heat and moisture and the anchoring of major storm tracks in the area of its influence (Kwon et al., 2010). The influence of these factors has been shown in studies of modern climate shifts (Byshev et al., 2024) and has been manifested at the paleoscale (Park et al., 2017; 2023; Ding et al., 2022). These processes were important in the monsoon dynamics of the Late Holocene. Typically, during Holocene cooling and during El Niño activation, SST in the tropical Pacific declined, leading to the summer monsoon weakening and a significant decrease in the intensity of cyclogenesis (Park et al., 2023).

The obtained record indicates more complex situations on the coast in the last two millennia than in the inland parts of the southernmost Primorye (Razjigaeva et al., 2021). The high-resolution record of paleoclimatic events shows a combination of trends in background temperature and humidification, sometimes synchronous, sometimes multidirectional, which was not always reflected in

the records obtained for nearby areas of Primorye and northeastern China. The paleoclimatic data for Lotus Lake of the response of biotic components are closer to the reconstructions made for the coast of the Korean Peninsula and Jeju Island, where the Medieval Climate Anomaly was drier and the LIA was wetter (Park et al., 2017).

The summer monsoon intensity is increasing ~2100 cal yr BP affected Jingpo Lake area, northeastern China (Chen et al., 2015), did not manifest in the southernmost Primorye; moreover, precipitation decreased, and conditions became drier: terrigenous supply into the lake and the number of planktonic diatoms decreased. There were no sharp increases in SST (Stott et al., 2004), and Kuroshio Current intensity decreased (Ding et al., 2022). During this time, El Niño intensity increased (Conroy et al., 2008), which, based on modern observations, can influence the precipitation decreasing. In years of strong El Niño, the intensity of the summer monsoon decreased and the activity of the winter monsoon increased (Byshev et al., 2014).

The moistening decrease is traced to the transition period (1800–1700 yr BP) and the beginning of cooling (1700–1600 yr BP), comparable to the Kofun period in Japan (1710–1220 yr BP) (Sakaguchi, 1983) and the global cold event (1650–1450 yr BP) (Wanner et al., 2011). Total solar irradiance (TSI) decreased (Steinhilber et al., 2009), the land temperatures (Klimenko et al., 2000; Ljungqvist, 2010) and SST of the western tropical Pacific were lower (Stott et al., 2004), a weakening of the Kuroshio Current was observed (Ding et al., 2022), and El Niño was activated (Conroy et al., 2008) (Fig. 5q, s).

The subsequent watering of Lotus Lake and increase in precipitation could be due to the activation of the Kuroshio Current (Ding et al., 2022), which promoted the penetration of warm humid air masses to the coast of the southernmost Primorye. This influence did not extend inland – a decreasing of the summer monsoon intensity was noted in northeastern China at this time (Chen et al., 2015).

A slight watering of Lotus Lake with more active river inflow occurred 1600–1230 yr BP. An increase in the proportion of planktonic species indicates the activation of typhoons 1300–1230 yr BP. The increase in wetting in Eastern Primorye was recorded approximately at this time (~1310 yr BP) (Razjigaeva et al., 2025b).

On the coast of Peter the Great Bay, the hydrological conditions in the development of lakes were unstable; both periods of watering and drier phases were distinguished (Lyashchevskaya et al., 2023; Razjigaeva et al., 2025a). Small islands in the southernmost part of Japan (Kamikoshiki Island) were wet ~1700–1480 yr BP, then wetness decreased (van Soelen et al., 2016), the larger islands experienced frequent flooding during the Kofun Period (Sakaguchi, 1983). Apparently, the main tracks of typhoons and deep cyclones passed here.

The beginning of active swamping of Lotus Lake shores (1230–1100 yr BP) coincided with the cooling trend, well expressed on the solar activity curve and paleotemperature curve (Fig. 5j, k). The age is similar to cold event “1b” (1350–1120 yr BP) of the northern hemisphere (Gorbarenko et al., 2024). At this time, El Niño activation occurred in the Pacific (Moy et al., 2002). Decreasing precipitation led to a lesser terrigenous supply into Lotus Lake. The slight watering (1040–980 yr BP) corresponded to a sharp increase in TSI (Steinhilber et al., 2009) and a temperature peak (Klimenko et al., 2000; Ljungqvist, 2010). At this time (1075 yr BP), the dry period on the Shufan Plateau (East Manchurian Mountains) ended (Razjigaeva et al., 2021). Watering of Gniloe Lake on the Nakhodka Bay coast was recorded at ~1060 yr BP

(Lyashchevskaya et al., 2023). In southernmost Japan, a short-term increased recurrence of strong typhoons was recorded at this time (Woodruff et al., 2009).

The sharply variable moisture regime with long dry seasons, observed in the southernmost Primorye in the second half of the Medieval Climate Anomaly, was probably also related not only to the increase in evaporation under warmer conditions than the present but also to the influence of El Niño. The spatial pattern of moisture change in the region was not uniform. In the area of Lotus Lake and to the north (the Boisman Bay), the decrease of peatland watering was recorded at 945–830 yr BP. Wet conditions on the Nakhodka Bay coast were 1060–840 yr BP and became drier 840–730 yr BP (Lyashchevskaya et al., 2023). On the coast of Eastern Primorye, the Medieval Climate Anomaly was humid (Nazarova et al., 2021). On the Korean Peninsula, according to annals, the recurrence of droughts increased 950–870 yr BP: it was dry on Jeju Island. This is attributed to the El Niño influence, changes in SST in the Philippine Sea and in the western tropical Pacific, which controlled the direction of tropical cyclone tracks (Park et al., 2017). Significant decreases in rainfall associated with reduced typhoon generation in the western Philippine Sea under the influence of El Niño have also been observed along the coast of eastern China and southern Japan (van Soelen et al., 2016; Park et al., 2017).

The unstable climate during the LIA, recorded in Lotus Lake section by frequent changes of watering and shallowing phases, was related to both abrupt, rapid changes in solar activity and high dynamic processes in the low latitudes of the western Pacific, where significant SST variations were observed (Stott et al., 2004). At the beginning of the period, the change from El Niño to La Niña regime occurred (Moy et al., 2002). The Siberian High became strongly activated ~700 yr BP (Mayewski et al., 2004), leading to the intensification of the winter monsoon, which blocked the penetration of cyclones coming from the sea, which was manifested in the development of “dry” winter seasons. In the first half of the period, the intensity of the Kuroshio Current decreased (Ding et al., 2022), which could reduce the meridional transport of moist air masses.

In the southernmost Primorye, the cooling of 800–630 cal yr BP accompanied by a decrease in precipitation coincided with the Wolf minima (Wanner et al., 2022), well expressed on the solar activity curve. During El Niño activation, tropical SST decreased significantly, and Kuroshio Current activity also decreased (Fig. 5p–s). The drier conditions favored the passage of fires 740–690 yr BP. The chronological framework of this dry period compares well with the long period (770–630 yr BP) of the most severe droughts during the last millennium in Korea, as chronicled in annalistic records (Park et al., 2017).

In general, during the LIA, moisture content increased in the southernmost Primorye. There was a tendency for intensification of the Siberian High intensity (Fig. 5i). The drier conditions of 520–410 and 350–300 yr BP were observed when the intensity of the summer monsoon decreased, as recorded in the lake deposits of Russky Island (Razjigaeva et al., 2024) and pollen records from northeastern China (Li et al., 2011). At this time, solar activity was weakening (Steinhilber et al., 2009), the Siberian High had the greatest intensity (Mayewski et al., 2004), and tropical SST significantly decreased (Stott et al., 2004). The Kuroshio Current weakened ~350–300 yr BP (Jian et al., 2000). The decrease in humidification 240–170 yr BP was of roughly the same nature.

On the Korean Peninsula and in Japan, the LIA was also wet. There is also similarity in the manifestation of dry

periods. According to annals, decreasing typhoons and prolonged droughts were observed 530–430 yr BP (Park et al., 2017). In southwestern Japan, wetting decreased ~300 yr BP (van Soelen et al., 2016).

CONCLUSIONS

The development of Lotus Lake over the last 2460 years was largely determined by hydroclimatic changes associated with the monsoon circulation dynamics. Processes in the western part of the tropical Pacific had a great influence. The analysis of the lake record indicates a strong variability in the intensity of the East Asian summer monsoon on a multidecadal scale. The manifestation of El Niño and the change in the activity of the Kuroshio Current were a great factor, which determined the spatial differences in the manifestation of separate events and strongly influenced the cyclogenesis.

The periphery of Lotus Lake represents a classic example of lake overgrowth and peatland formation. The diatom flora reacted to the discontinuance of connection

with the sea ~2100 yr BP, which caused a change in the geochemical environment in the lake. Several periods of increasing and decreasing lake watering up to the formation of a sedge swamp 1650–1600 cal yr BP at the beginning of global cooling has been identified. The most dramatic changes in the shore zone with the formation of a green moss swamp occurred 1230 yr BP during the trend to short-term cooling and El Niño activation. There has been considerable variability in environments during the last millennium, and ecological factors changed particularly frequently and sharply during the LIA. Drying tendencies have been noted at solar activity minima. The course of hydroclimatic changes, reconstructed on the response of biotic components of Lotus Lake, was closest to the paleoclimatic situation on the Korean Peninsula coasts and Jeju Island. High-resolution paleoclimatic reconstructions indicate that changes in the regional natural environment were significantly influenced by the complex interaction of such important drivers as variations in solar activity, large-scale atmospheric circulation, and paleoceanological conditions in the low latitudes of the Pacific. ■

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HISTORICAL LAND SYSTEMS OF RUSSIA: TRENDS, BIASES, AND GAPS IN THE LITERATURE

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ABSTRACT. This paper presents a systematic literature review of 210 peer-reviewed studies to analyze the state and trends of Land System Science (LSS) research on historical land use and land cover change in Russia from 2000 to 2024. The review reveals a significant and persistent geographical bias, with the vast majority of case studies concentrated in the European part of Russia (e.g., Belgorod, Tula, Moscow regions), while vast areas of Siberia, the Far East, and the Arctic remain critically understudied. Thematically, research is dominated by studies on agricultural land abandonment and forest landscape dynamics, with urban landscapes receiving scant attention. Long-term studies covering periods of more than a century are prevalent. However, their analytical depth is often limited by reliance on historical surveys or aggregated statistics. Satellite remote sensing, especially Landsat images, is the most common source of data. These images are often combined with other types of data. The use of historical cartographic sources (e.g., General Land Survey plans) is hindered by issues of accessibility, digitization, and often insufficient thematic detail for comprehensive landscape analysis. Consequently, studies often use just two time points and a single spatial scale, typically based on administrative rather than biogeographical units. The review identifies a clear linguistic and international visibility gap: 82% of publications are in Russian only, and a substantial portion appear in journals not indexed in international databases, limiting their global integration. Furthermore, a concerning number of studies (74%) do not systematically analyze the driving forces behind the observed landscape changes. This synthesis underscores the urgent need to address regional research disparities, enhance the methodological depth by integrating multi-source historical data and robust causal analysis, and improve the international accessibility of Russian LSS research. By doing so, the Russian LSS community can not only fill critical knowledge gaps within the country but also make a more substantial contribution to global land change science, offering unique insights from its vast and diverse socio-ecological systems.

KEYWORDS: land use land cover change, historical land change, landscape dynamics, old maps, land system science, long-term socio-ecological research

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INTRODUCTION

Land-use change is one of the most significant drivers of environmental transformation, with profound and often nonlinear impacts on ecosystems, biodiversity, and socio-economic stability (Foley et al. 2005; Lambin et al. 2001). From deforestation to urbanization, these changes threaten the resilience of both natural systems and human societies, necessitating integrated scientific approaches to understand and mitigate their effects. LSS has emerged as a critical interdisciplinary field to address these challenges, combining insights from geography, ecology, economics, and political science (de Bremond et al. 2019; Grove and Pickett 2019; Turner et al. 2007). By analyzing the interactions between human activities and landscapes, LSS provides a framework for sustainable land management and policy development. However, while global syntheses

exist, regional disparities in research coverage persist (Boillat et al. 2017; Liu and Tian 2010; Newbold et al. 2015) – particularly in vast and ecologically diverse regions like Russia, where land-use dynamics remain understudied in international literature.

Russian researchers have made notable contributions to understanding global environmental change, particularly in paleogeographic and paleoecologic reconstructions (Borisova 2021; Filimonova 2021; Novenko et al. 2019; Velichko et al. 2016), boreal forest carbon dynamics (Arkipova 2020; Chernova et al. 2018; Dolman et al. 2012), and permafrost-climate feedbacks (Broushkov et al. 2024; Romanovsky et al. 2010). Their work has been instrumental in IPCC assessments and global carbon cycle modeling (Kurganova et al. 2024; Kuricheva et al. 2023). Notably, the TEEB Russia initiative (Bukhareva et al. 2019, 2021) advanced ecosystem services (ES) valuation at national and

regional scales, highlighting Russia's vast natural capital. Recent systematic reviews on urban ecosystem services in Russia (Dushkova et al. 2025), demonstrate progress in synthesizing fragmented research, though challenges persist in translating findings into policy. However, research on historical land-use patterns remains underdeveloped compared to Western Europe and North America, creating challenges for integrating Russian data into global models (Ellis et al. 2010; Hurtt et al. 2011; Klein Goldewijk and Verburg 2013). This gap limits comprehensive assessments of anthropogenic impacts on Russia's landscapes and their role in global environmental change.

Russia, the world's largest country by land area, plays a pivotal yet underappreciated role in global environmental processes, from carbon sequestration in boreal forests to the conservation of Arctic ecosystems (Danilov-Danilyan et al. 2023; Tishkov 2012). Its unique drivers of land-use change – such as post-Soviet agricultural abandonment, industrial expansion in Siberia, and climate-driven shifts in permafrost – differ markedly from those in Europe or North America (Gunya 2017; Lyuri et al. 2010; Prishchepov et al. 2020). Despite this, global syntheses do not adequately represent Russia's land-system research. This gap limits the integration of Russian data into international models. It also obscures the country's contributions to key debates on biodiversity loss, climate adaptation, and sustainable development. Bridging this divide requires not only greater access to Russian research but also targeted collaborations to highlight its distinct socio-ecological trajectories.

Russia's environmental heterogeneity – from the steppes of the European Plains to the taiga of Siberia – has fostered diverse land-use practices shaped by climatic constraints, institutional policies, and historical contingencies (Josephson et al. 2013; Moon 2013; Smirnova et al. 2017; Trapeznikova 2017). For example, the Soviet Virgin Lands Campaign of the 1950s transformed vast grasslands into croplands, while post-1991 market reforms led to widespread farmland abandonment and forest regrowth (Kraemer et al. 2015; Prishchepov et al. 2013; Schierhorn et al. 2013). These shifts were further modulated by regional factors, such as soil fertility in the European south or permafrost instability in the Far East. Nevertheless, research remains fragmented, with strong biases toward European Russia (Alix-Garcia et al. 2016; Matasov et al. 2019; Vampilova and Sikan 2023) and limited attention to the Urals, Far East, and Arctic (Aleinikov 2021; Bocharnikov, Steblyanskaya 2022; Belousova 2024; Bergen et al. 2020). Compounding this, Russia's scientific traditions emphasize localized, qualitative case studies over quantitative meta-analyses, reflecting both methodological preferences and data limitations.

A critical barrier to understanding Russia's land-use history is the scarcity of accessible, high-resolution historical data. Despite the existence of extensive cartographic resources, their development was highly uneven, shaping strong geographical and temporal biases in research possibilities (Alyabina et al. 2015; Goldenberg and Postnikov 1985). Pre-revolution materials include the General Land Survey (*Generalnoye mezhevaniye*) plans (1765–1888), covering 36 provinces and providing key insights into pre-industrial land use; the detailed Mende maps (1847–1867) of central regions; and military topographic maps such as the Three-Verst Map (1:126,000), the Ten-Verst Map (1:420,000), and maps of the Caucasus, which offer valuable though often generalized landscape information (Golubinsky et al. 2011; Kusov 1993; Postnikov and Melnikova 1980). The Soviet period introduced detailed State Topographic Maps (*Genshtab* maps) and various thematic maps. These

included forest inventories, agricultural land use maps, and land management (*Zemleustroitel'naya*) plans. While they systematically covered vast territories, their primary purpose was often administrative (Dolgov et al. 2018).

However, the application of these materials in systematic land system science faces major challenges. Significant portions of the cartographic legacy, especially large-scale Soviet-era maps, remain difficult to access due to archival restrictions and fragmented preservation. Moreover, only a small part of them has been digitized and georeferenced to modern standards, limiting their use in GIS-based analyses (Golubinsky et al. 2013; Matasov 2016). Thematic inconsistency across time and regions, a focus on economic or military features rather than ecological detail, and a pronounced decline in map coverage east of the Urals further constrain research. While remote sensing (e.g., Landsat) has partially compensated for these gaps by capturing changes since the 1980s (Ershov et al. 2022; Gutman and Radeloff 2017), it cannot illuminate earlier critical transitions, such as those during the Soviet era. Thus, integrating multi-temporal cartographic sources with satellite data, developing unified national datasets, leveraging GIS technologies, and fostering collaborations between historians, ecologists, and remote-sensing experts could unlock new insights into Russia's land-system resilience and vulnerabilities.

Thematic priorities in Russian land-use research often diverge from western LSS, with a stronger focus on soil degradation (Chendev et al. 2023; Chernova et al. 2018), local landscape typologies (Khoroshev and Dyakonov 2020), palaeoecological and historical reconstructions (Kosenkov and Kolbovsky 2012; Novenko et al. 2017; Shilov and Kozlov 2019) rather than globalized drivers like commodity markets or telecoupling. This divergence reflects both contextual differences and the isolation of Russian academia, where the majority of studies are published in domestic journals (e.g., *Izvestiya RAN. Seriya Geograficheskaya*) with limited international indexing. Linguistic barriers further exacerbate this disconnect, as few Russian researchers engage in English-language publications or global networks like the Global Land Programme. To address this, systemic support for translation, open-access publishing, and comparative studies is essential – not only to elevate Russia's scientific visibility but also to enrich global LSS with its unique empirical and theoretical perspectives (Meyfroidt et al. 2018; Verburg et al. 2013).

In our systematic literature review, we aimed to analyze various publications on LSS in Russia to address the main research question: what is the current state of research on historical land use in Russia? To achieve this goal, we formulated the following subquestions. First, we sought to identify the methodological approaches used to assess historical changes in land systems across different regions of Russia. This involved grouping various research approaches by identifying key research areas, methods, and objects of the studies. Second, we aimed to determine the main pathways of historical LSS development in Russia. This included classifying and describing typical research studies and identifying the principal directions for further development in this field.

The paper consists of several sections: the methodology presents a location-based context, describes the general approach used in the study, and provides an overview of the materials (data sources) and methods employed, explaining the literature review steps. The results section offers a detailed examination of LSS terms used in Russian scientific literature and specifies general patterns observed

in the reviewed studies. The analysis of case study research encompasses two domains: spatial distributions and thematic analyses of these studies. Finally, a qualitative analysis of the most frequently cited studies is provided to summarize and systematize the findings, which are also critically reflected in the discussion section.

MATERIALS AND METHODS

Data Sources and article search

Our method followed established guidelines for systematic review and systematic mapping and was inspired by previous systematic review exercises in comparable fields (Dushkova et al. 2025; Herrero-Jáuregui et al. 2018; Plieninger et al. 2016). We focused on Russian- and English-language peer-reviewed articles published in international and Russian scientific journals between 2000 and 2024. Research results published in dissertations, monographs, textbooks, and regional planning documents were excluded from this review. The search for English-language articles was conducted using the Scopus, ISI Web of Science, and ResearchGate databases. For Russian-language studies, we used the Russian Scientific Electronic Library eLIBRARY¹ and CyberLeninka². The search was performed using the following terms and their analogues in Russian and English: “land use”, “land use change”, “cultural landscape”, “agrolandscape”, “forest / agricultural landscape transformation”, “land use system”, “forest dynamics”, “geosystems”, “development stages”, “settlement system”, “anthropogenic transformation”, “cropland abandonment”, “land use system”, “reforestation”, “long term change”, “forest degradation”, “forest fragmentation”, “transformation of landscapes”, “historical reconstruction”, “landscape dynamics”, “historical geography”. Search terms were entered into the publication title, abstract, and keywords. The same filter was used for both international and Russian databases. After verifying the correct display of search terms and removing language duplicates, the search yielded 412 works selected for the next stage of the screening process.

Based on the works of Geist and Lambin (2002), Magliocca et al. (2015), Plieninger et al. (2016), we defined four inclusion criteria for articles: the study had to (1) describe a landscape that has undergone changes over a period of at least 30 years; (2) provide analysis of research results based on methodology for quantitative or qualitative measurement of landscape change processes; (3) focus on the territory of Russia at regional and local scales (within its borders as of the year 2000), conducted by Russian researchers or with their participation; and (4) offer explanations for the causes of landscape change. Thus, research based on social and economic analysis, theoretical works, geographically unattached, conceptual, and summarizing publications was excluded. A sample of 210 scientific articles was finally included in the review for subsequent spatial and thematic analysis.

Data analysis

To analyze keyword trends and map research themes, we used VOSviewer software³. We applied the co-occurrence analysis method, which clusters keywords based on how frequently they appear together in publications. This shows the strength of relationships between terms. In the resulting visualizations, the size of a node represents how often a keyword is used, and the thickness of the connecting

lines indicates how strong the link between two terms is. The color of a node indicates its cluster. Shorter distances between nodes represent stronger relationships between keywords.

We used a standardized data extraction sheet to systematically categorize each study. This sheet recorded general parameters and key attributes such as the spatial focus of the research, the scale of analysis, the types of data sources used, the methodological approach, etc. (Table 1).

The analysis considered the number of spatial scales in each study. We defined two types: single-scale studies (e.g., focused on one specific region or site) and multi-scale studies (using two different spatial scales for analysis or modeling). Multi-scale studies are crucial for understanding complex systems where interactions at different levels influence overall dynamics. We also recorded the number of study sites and classified their boundaries into three types: administrative (e.g., regional borders), biophysical (e.g., watersheds), and author-defined (e.g., borders of satellite imagery scenes or cadastral map sheets).

For methodological analysis, we examined the types of source data and indicators used. Based on a preliminary review, we grouped the source data into six categories: 1) statistical data (official reports, statistical yearbooks); 2) literary sources (previously published articles); 3) historical maps (pre-1917 maps of various scales); 4) cadastral and thematic maps (topographic, land use, and planning maps); 5) solely Landsat; 6) satellite imagery (e.g., MODIS, CORONA, Sentinel). Data processing methods were classified into four groups: 1) descriptive (comparative analysis of published data); 2) statistical (mathematical processing of data); 3) geostatistical (spatial analysis and modeling); 4) custom methodology (author-developed approach). Each study was categorized based on these parameters. Studies employing a custom methodology were specifically noted.

Finally, we used descriptive statistics to identify the main driving forces of landscape change and their interactions. The categories for this analysis were pretested to ensure consistency. The statistical analysis was performed using R, and maps showing the spatial distribution of the studies were created in QGIS v4.20.

RESULTS

Overview of the keywords in articles

The co-occurrence of keywords indicates the prevailing research trends within the field. After consolidating synonymous terms and correcting errors, a final list of 231 unique keywords was compiled. From this list, 67 keywords occurring more than three times were selected for further analysis (Table 2). A co-occurrence network map was constructed from these keywords, which were subsequently grouped into nine distinct clusters, each denoted by a different color (Fig. 1). Within this network, the size of a node (representing a keyword) corresponds to its “total link strength”—a metric quantifying the strength of its connections to all other keywords. The lines between nodes represent the individual co-occurrence links between pairs of keywords. The central network area is dominated by larger nodes, indicating keywords with high frequency. The most prevalent keywords are “land use” (56 occurrences), “forest cover” (25 occurrences), “GIS” (24 occurrences), and “remote sensing” (21 occurrences). Finally, Table 2 lists the ten keywords with the highest total link strength.

¹URL: <https://www.elibrary.ru>, accessed on 20 January 2025.

²URL: <https://www.cyberleninka.ru>, accessed on 20 January 2025.

³URL: <https://www.vosviewer.com>, accessed on 6 August 2025.

Table 1. Variables used in the data extraction sheet

Variables name	Classes/Units
Authors Affiliation	institute, country
Article Language	Russian, English, Russian and English
Year of publication	number
Indexation base	RINC, core RINC, WoS or Scopus
Citations	number
Study region	country, administrative regions
Type of relief	plains, mountains
Land system	agro, forest, urban, mixed
Natural zone	boreal, hemiboreal, nemoral, steppe
Period, years	0–30, 30–100, >100
Number of study periods	2, 3–4, >5
Number of study areas	1, 2–3, >4
Number of scales	1, 2
Type of study area border	administrative, natural, user-defined
Data Source	statistical data, literature, historical data, maps, Landsat, other satellite
Methods of analysis	statistic, geostatistics, description, custom
Type of analysis	quantitative, qualitative, no analyze (statement)
Factors or drivers in study	social, natural, no factors

Table 2. Ten keywords with the maximum total link strength from VOSviewer

Keyword	Total link strength	Occurrences
land use	158	56
GIS	84	24
forest cover	74	25
remote sensing	74	21
reforestation	63	21
agriculture	56	21
satellite images	49	13
land use change	41	12
Landsat	41	14
arable lands	40	12

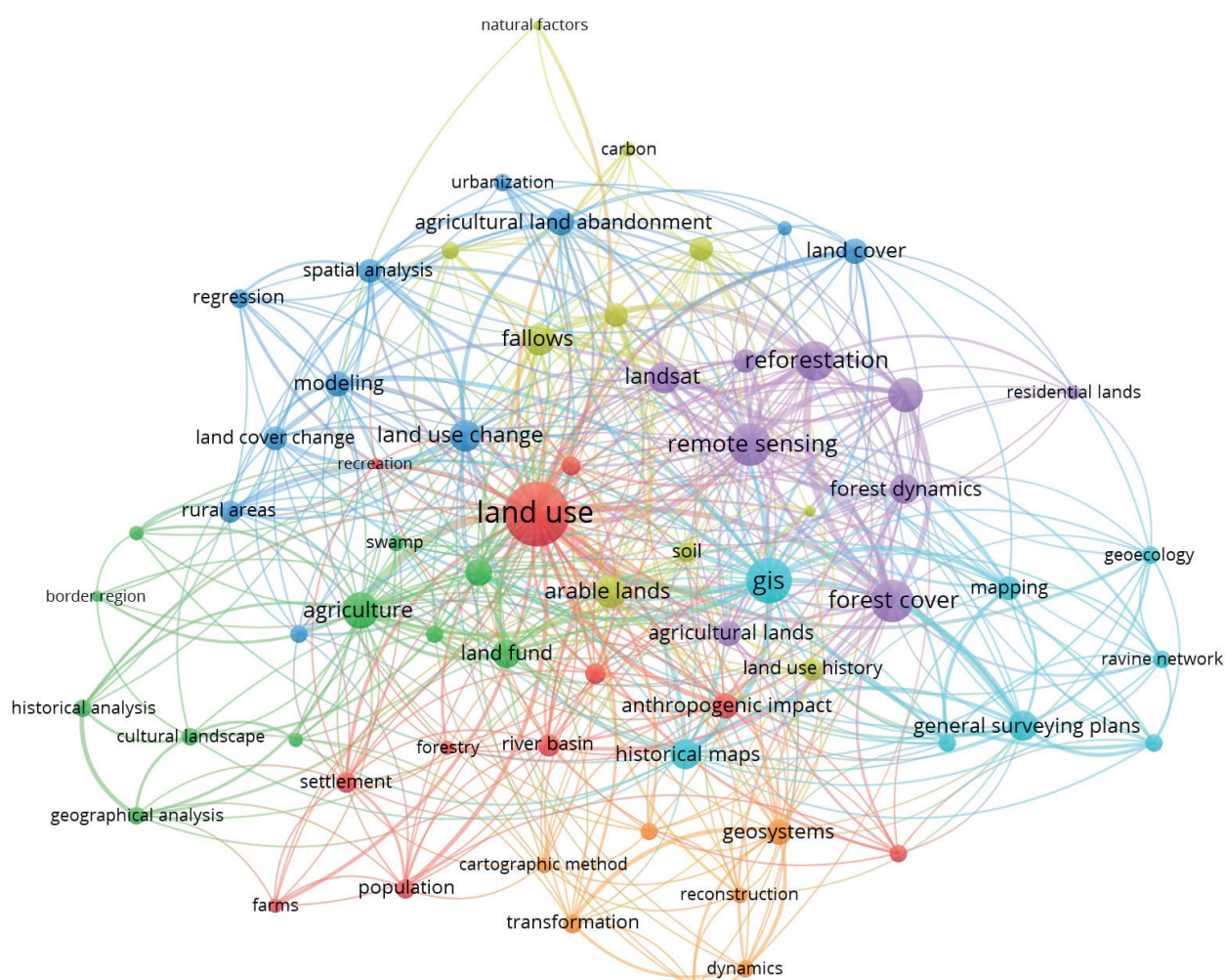


Fig. 1. Authors' keywords concerning LSS in Russia

The co-occurrence network analysis reveals a coherent intellectual structure within the domain of land change science, characterized by a central thematic core and distinct, interconnected methodological and thematic clusters. The pronounced centrality of "land use" and its dynamic counterpart, "land use change," establishes them as the principal research foci, functioning as the nexus to which all other concepts connect. This core is methodologically underpinned by a robust cluster comprising "GIS," "remote sensing," and "spatial analysis," signifying their indispensable role as the primary analytical framework for the discipline. The network further delineates specialized, yet interrelated, research streams: one cluster emphasizes ecological dynamics and forest transitions, investigating processes such as "reforestation" and "forest cover" change, often linked to drivers like "agricultural land abandonment." A parallel strand is dedicated to historical and reconstruction-based approaches, leveraging "historical maps" and "cartographic methods" to analyze long-term "cultural landscape" transformation and "anthropogenic impact." The clustering of keywords into distinct yet connected groups illustrates the field's multidisciplinary nature, integrating spatial analysis, landscape transformation studies, and historical reconstruction to understand the dynamics of land cover change driven by both anthropogenic and natural factors.

General and thematic overview

Our review identified a total of 210 case studies on land systems conducted by Russian researchers, focusing primarily on regions within Russia but also including some studies in neighboring countries. Analysis of publication

years shows a gradual increase in the number of studies, peaking in 2017–2018, followed by a decline to around 9–10 publications per year recently.

The vast majority of articles (82%) were published only in Russian, while 9% were published only in English, and another 9% were bilingual (published simultaneously in both languages). As shown in Fig. 2, the share of English-language and bilingual publications has varied over time. Since 2013, such publications have appeared annually, and in some years, they accounted for 50–60% of the annual total.

Another important indicator is the international visibility of Russian research, which we assessed based on indexing in international databases (IDB), particularly Scopus and Web of Science. During the first decade of the study period (2000–2011), only a few Russian journals were indexed in these databases. However, since 2012, annual publications of IDB-indexed articles have ranged from 10% to 55% (Fig. 3).

The studies were published in 124 different journals, most of which are multidisciplinary, covering fields such as geography, environmental science, ecology, agriculture, forestry, and remote sensing.

Most studies (96%) focused on territories within Russia, with a small number including areas in neighboring countries such as Ukraine, Belarus, Kazakhstan, Estonia, Lithuania, Latvia, Poland, and even the United States. The overwhelming majority of studies (182 out of 210) were conducted within a single Russian region. Only a few studies covered two, three, or five regions. The highest number of studies (24) were conducted in Belgorod Oblast, followed by Tula and Tambov Oblasts (19 each), Moscow Oblast

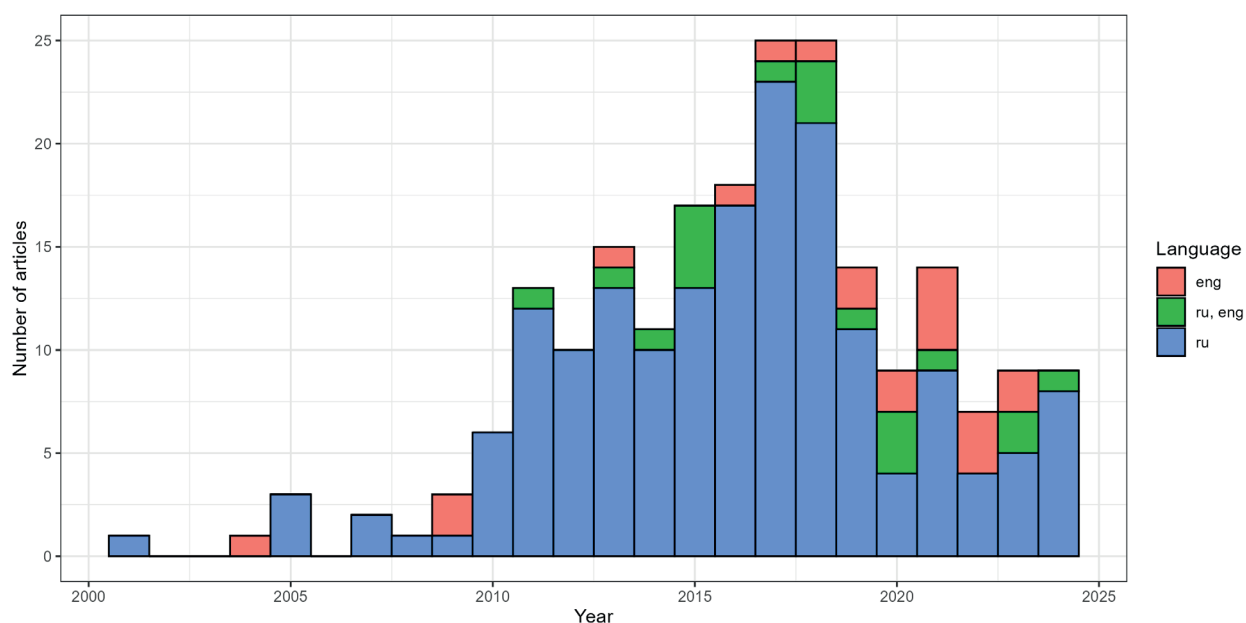


Fig. 2. Temporal distribution of the analyzed articles, separated by language

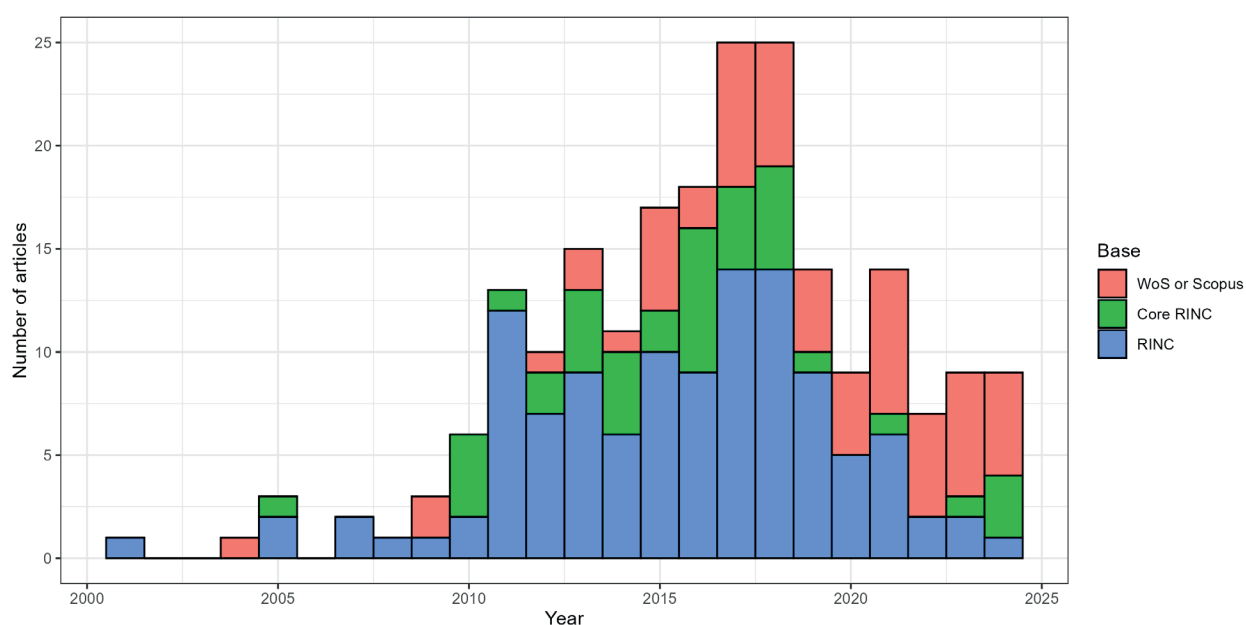


Fig. 3. Temporal distribution of the analyzed articles, separated by IDB indexing

(18), and Perm Krai, Ryazan Oblast, and Smolensk Oblast (16 each) (Fig. 4). The fewest studies were conducted in Siberian regions (with the exception of Irkutsk Oblast and Zabaykalsky Krai) and the Russian Far East. Studies covering the entire territory of Russia were rare.

The vast majority of studies (85%) were conducted in plain landscapes, while significantly fewer (13%) focused on mountainous areas, and only 2% included both landforms. Studies on agricultural land dynamics dominated the research period, followed by forest landscapes, which were studied half as frequently. Very few studies focused on urban landscapes or integrated analyses of all three landscape types (Fig. 5).

Analysis of the biogeographical distribution of study sites showed that more than half were located within a single natural zone. Most sites were in the nemoral and boreal zones; fewer were in the hemiboreal zone, and even fewer in steppe zones. About 20% of studies covered two, often adjacent, zones. Studies spanning three or more natural zones were rare (Fig. 6).

The overwhelming majority of studies (74.2%) were conducted within a single site or polygon, while only a small number used multiple sites (Fig. 7). Most studies also

used only one spatial scale of analysis (Fig. 7). Administrative boundaries were the most commonly used type of study area delineation (62% of studies), often reflecting modern municipal or regional borders, and less frequently historical districts or provinces, largely due to the reliance on statistical data tied to administrative units. User-defined boundaries, such as satellite image scenes or thematic map extents, were used in about 25.4% of studies. Natural geographical boundaries, such as river basins, were used least frequently (12.7%).

The size of the study areas varied from a few square kilometers to millions of square kilometers. More than half of all studies were conducted at a regional scale, covering areas larger than 1,000 km² (Fig. 7). This preference was closely linked to the data sources used: statistical data, literary reviews, and medium-resolution satellite imagery (Fig. 8).

Analysis of data sources revealed that statistical data were the most commonly used, due to their ease of processing and availability. Medium-resolution satellite images (e.g., Landsat) were the second most frequent source, widely used for assessing agricultural and forest landscape dynamics over the past 30–40 years. Literary reviews ranked third. Beyond these primary sources, 28 different combinations of data

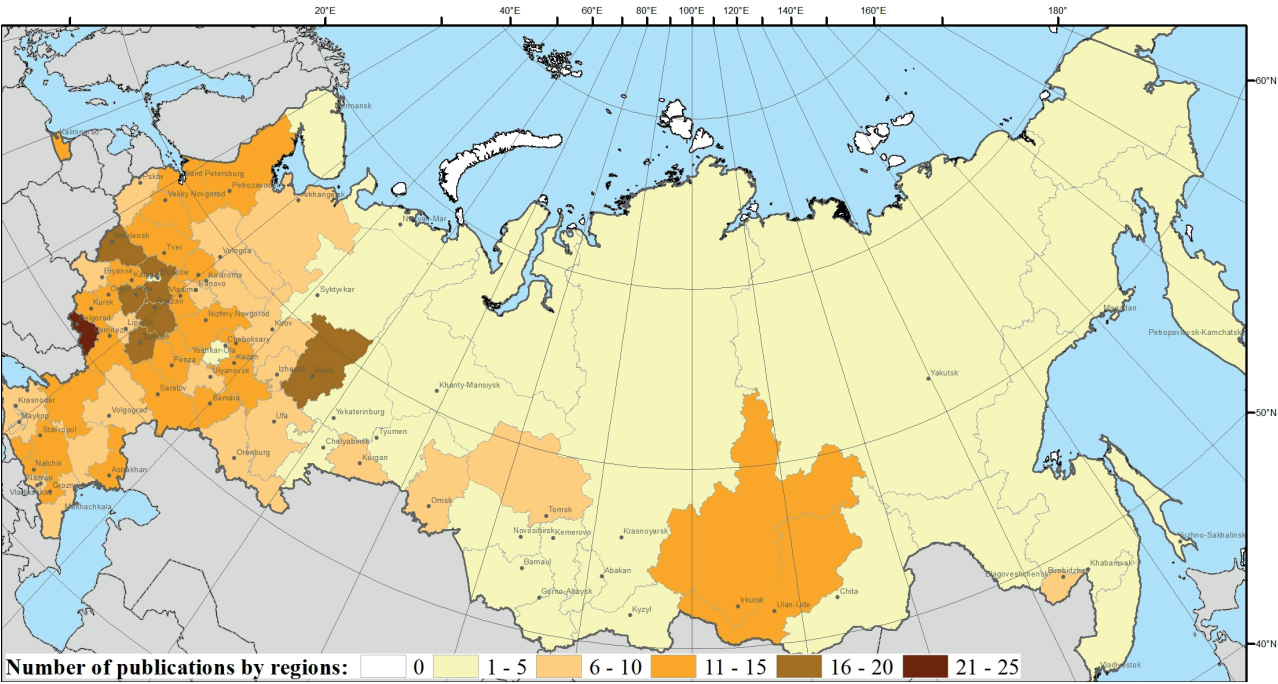


Fig. 4. Number of publications by Russian regions from 2000 to 2024. The borders of Russia as of 2000

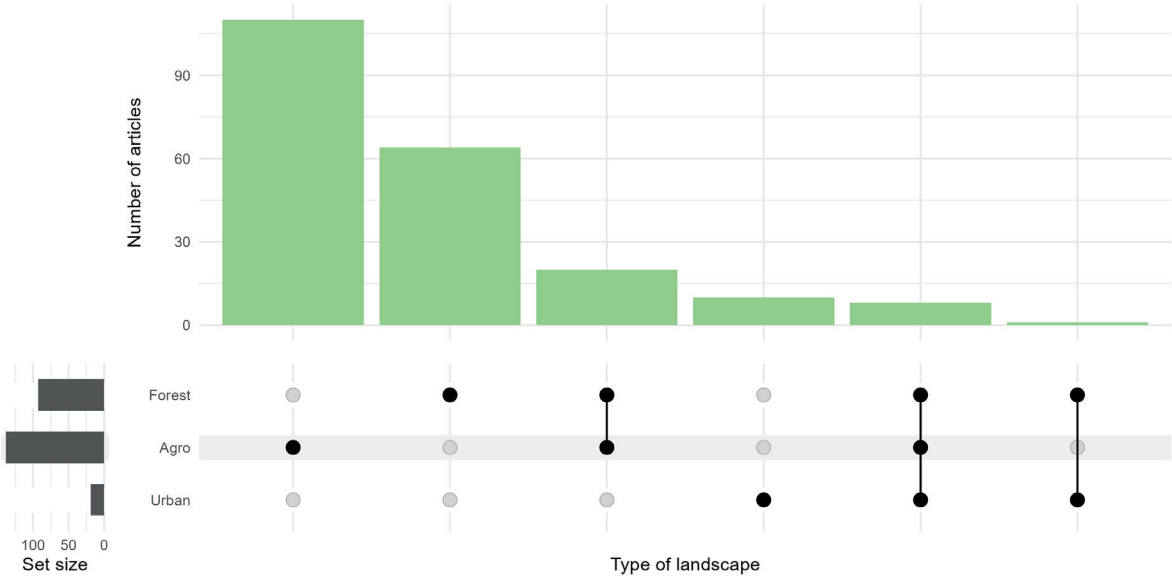


Fig. 5. The distribution of articles by type of studied landscape

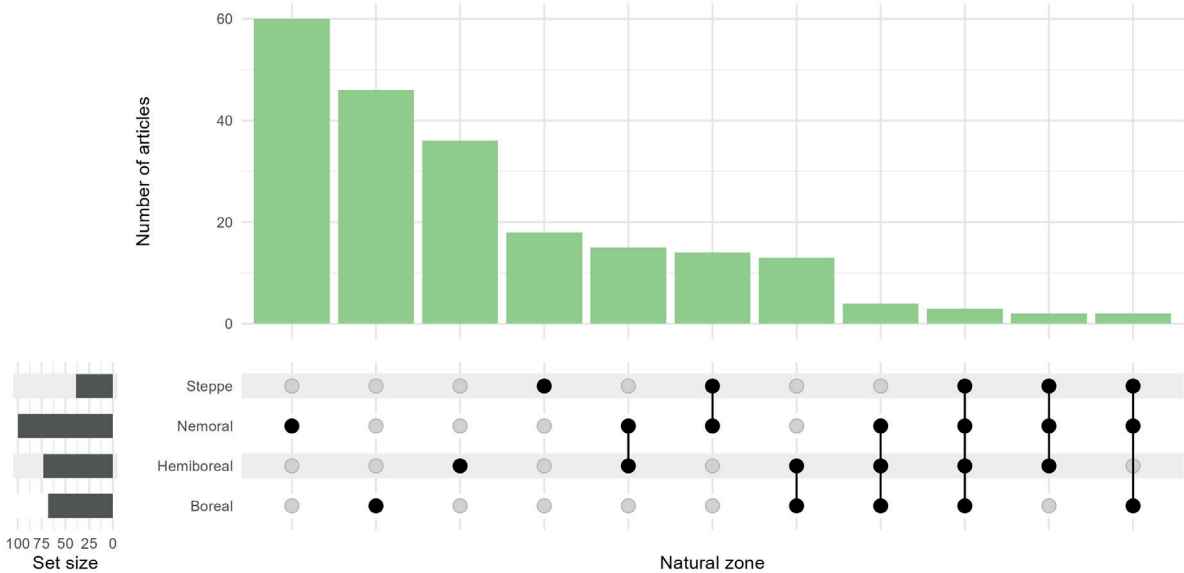


Fig. 6. The distribution of articles by location in natural zones

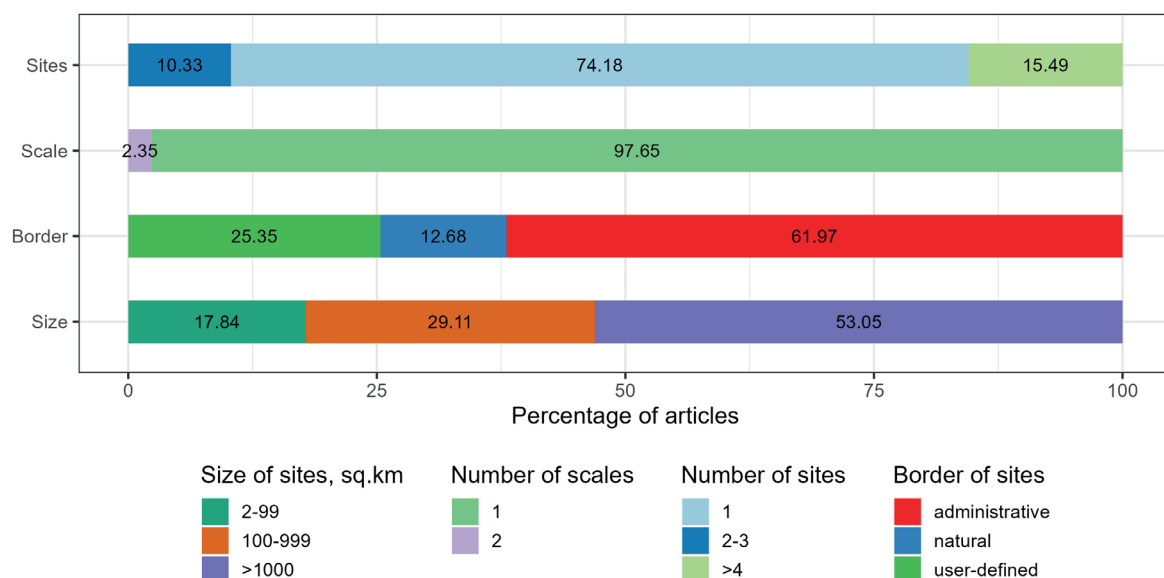


Fig. 7. The distribution of studies by spatial scale, number and size of sites, as well as the nature of their boundaries

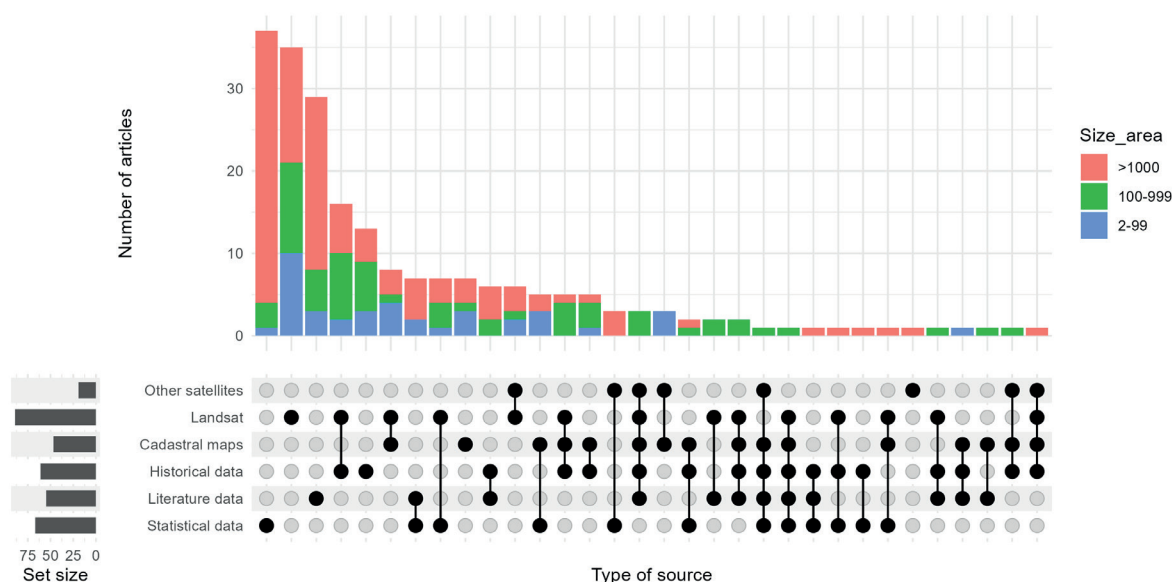


Fig. 8. Distribution of articles by data sources and object sizes

sources were identified. The most frequent combination was Landsat imagery paired with historical maps, used to represent two time points (Fig. 8).

The reliance on remote sensing and cartographic data led to a predominance of geostatistical processing methods. Descriptive (including personal interpretation) and statistical methods were the second and third most common, respectively. Many studies used combinations of these three main methods, reflecting the use of multiple data sources (Fig. 9).

Analysis of the time depth of the studies showed a focus on long-term changes (over 100 years; 43.2% of studies). Short-term (up to 30 years) and medium-term (30–100 years) changes were studied less frequently (31.9% and 24.9%, respectively) (Fig. 10). Most studies using satellite imagery or General Land Survey data were limited to two time points: historical and contemporary. Studies based on statistical or literary reviews were able to incorporate a greater number of time slices.

Analysis of study parameters revealed a clear trend toward an increasing number of studies providing quantitative analysis of land dynamics (Fig. 11).

Analysis of the drivers of change showed that the vast majority of studies did not investigate causal factors. Among those that did, social factors were most frequently

identified as the main drivers, while natural factors played a significantly smaller role (Fig. 12).

Overview of several typical groups

Based on a methodological analysis of the studies, we identified several distinct types of research, categorized according to their primary data sources and the depth of historical generalization.

Review of Land Use History

This category comprises publications that describe the history of settlement, land development, and the typology, characteristics, and periodization of land use over different historical periods. A significant number of works are dedicated to reconstructing past landscape development. These studies are typically based on the analysis of available historical literature and archaeological findings. They are often large-scale, long-term reviews without precise geographical referencing. A classic example is an article by Levchenkov (2016), which provides a comprehensive historical overview of the Kaliningrad region's development from the 13th century, illustrating the formation of its cultural landscape for each historical period. Fetisov (2014)

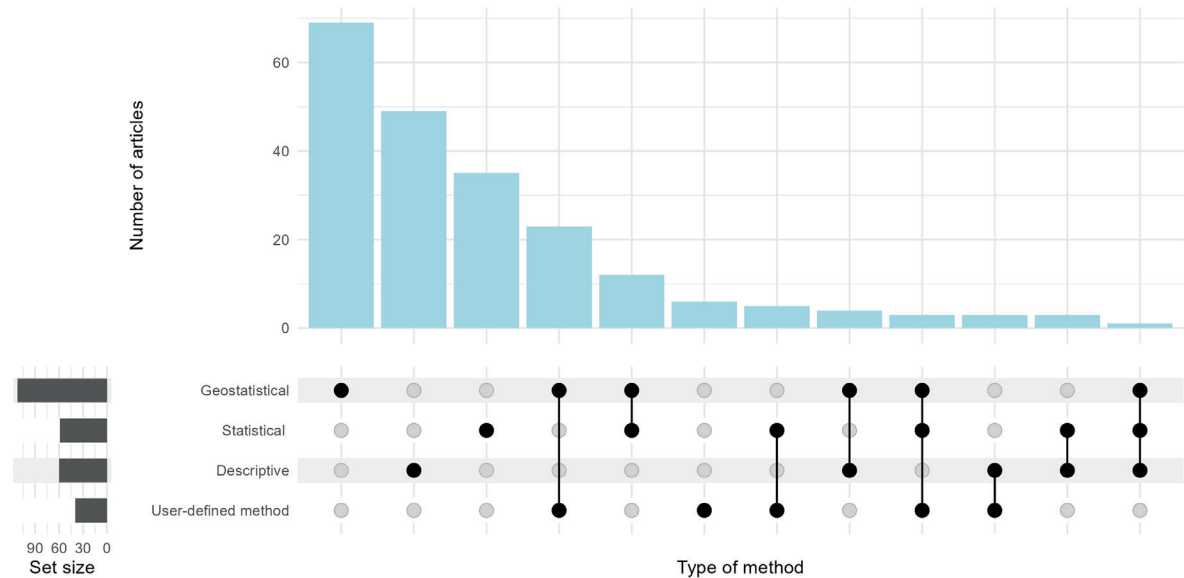


Fig. 9. Distribution of articles by used methods

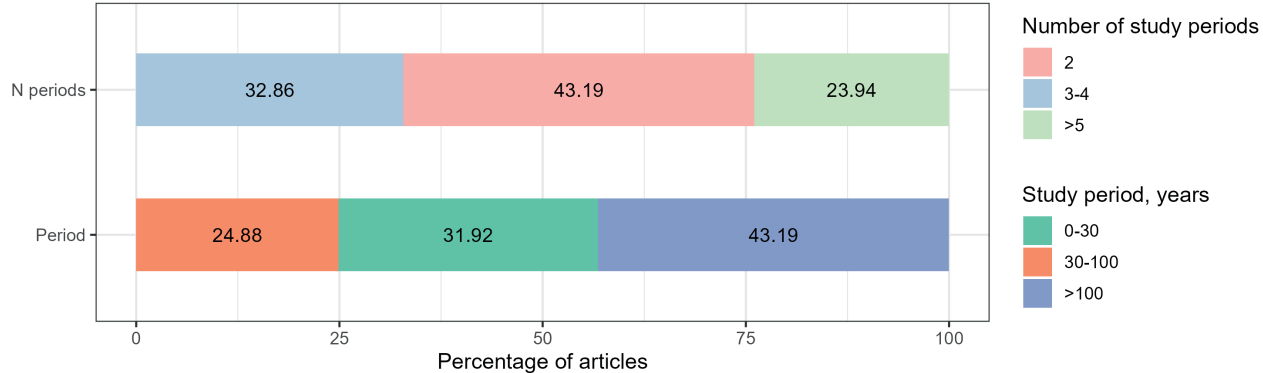


Fig. 10. The distribution of articles by the number of analyzed periods and the time-depth of research

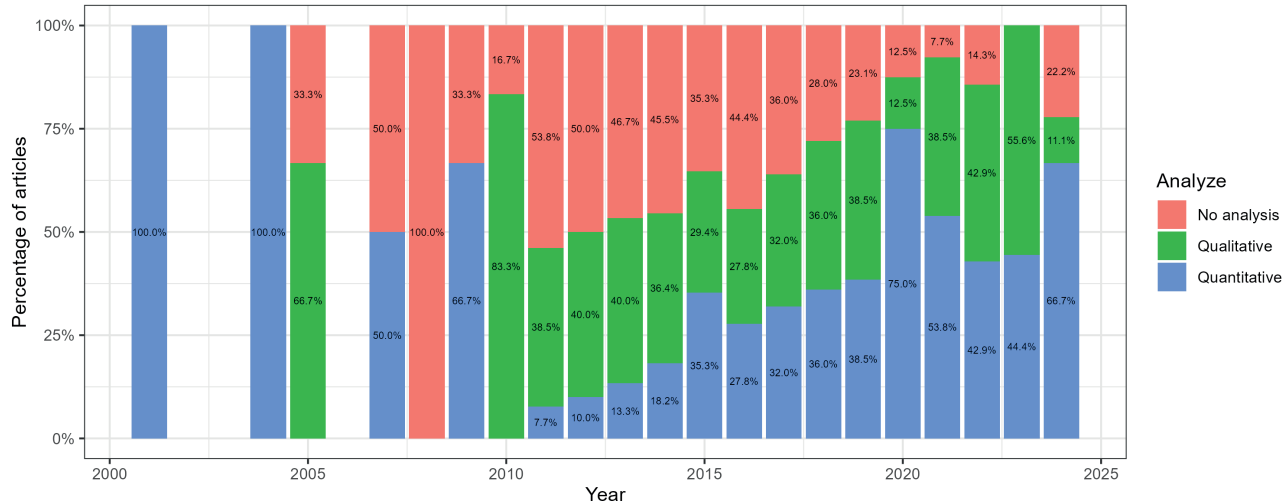


Fig. 11. Temporal distribution of the articles, separated by the type of analysis

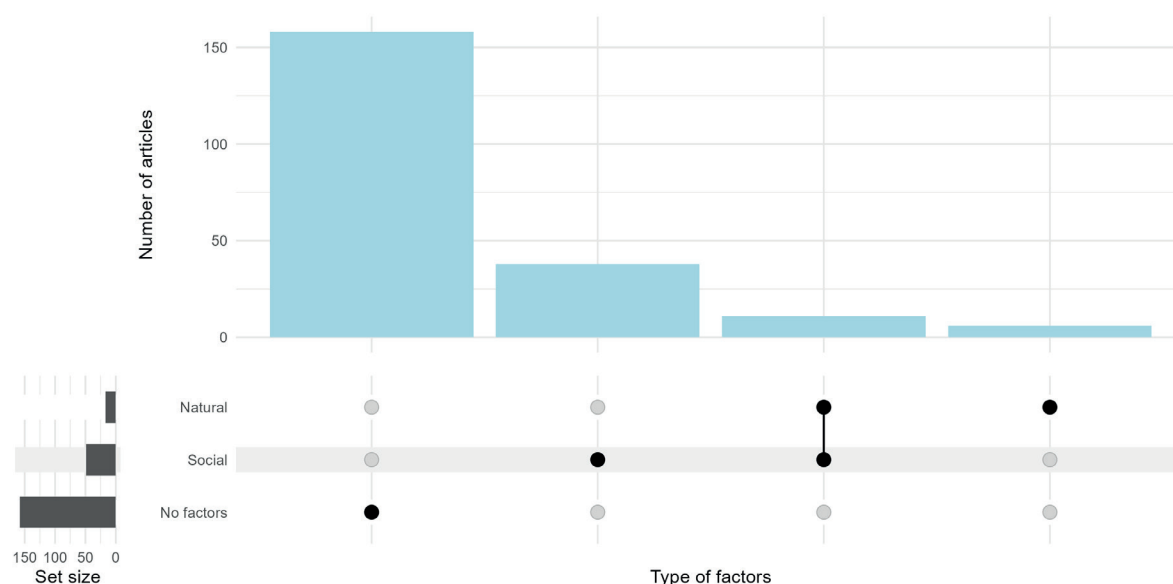


Fig. 12. The distribution of articles by the factors considered in the analysis

examined land use history in the Jewish Autonomous Region from the late 19th to early 20th centuries. They identified five development stages, created land use maps for each, and analyzed land area dynamics. Other studies have frequently utilized statistical reviews. For example, Vinogradova (2020b) calculated landscape composition ratios and changes in land use systems over 80 years in the Kaliningrad region. The study constructed maps showing the proportion of anthropogenic, natural, and recovering landscapes for ten historical time slices and calculated the Shannon diversity index and number of land use types.

Statistical Data Analysis

These are comparative historical studies based on statistical data (without cartographic materials) concerning the area of various land categories or forest cover over time. The temporal scope of these studies is limited by the availability of official statistics, and their geographical scope is often confined to administrative boundaries (municipalities or regions). For instance, Vinogradova (2020a) analyzed the dynamics of agricultural land use in Northwestern Russia and the Baltic countries from 1848 to 2018, mapping the ratio of cultivated agricultural land areas, assessing rates of change, tracing grain yield dynamics, and forecasting future agricultural development. Some studies tracked 5-7 land categories (e.g., agricultural, settlements, industry, protected areas, forest fund, water fund), as for the Akhtubinsky district of the Astrakhan region over 30 years (Barmin, Iolin, Sharova, and Golub, 2011), or for arable land, fallow, perennial plantings, hayfields, and pastures in the northern zone of the Omsk region from 1954 to 2011 (Makenova and Stepanov 2017). However, publications analyzing the dynamics of a single category, most often agricultural land and its subtypes, predominate. Some studies focused on forest cover dynamics, e.g., Musievskiy (2013) for the Voronezh region since the 16th century. Analyzing data across multiple regions allows for identifying regional differences, such as grouping regions in European Russia based on the ratio of sown area in 2013 to 2004 levels (Kitov and Tsapkov 2015); a similar typology was later applied to all of Russia (Lyuri et al. 2018).

Historical Map Analysis

This type involves reconstructing land and forest use through the analysis of historical maps. Frequently used

sources include the Materials of the General Land Survey (Plans General'nogo mezhevaniya), which record the state of territories in the late 18th century. Methodological approaches for analyzing and reconstructing the spatial structure of land use using this source are detailed in Matasov (2016). The method involves preparing outlines of individual landholdings, combining them into a unified coverage, transforming and georeferencing them to a modern base, reconstructing land use structure, and restoring the socio-economic infrastructure of the historical period. Numerous examples exist, such as Kukushkina (2018), reconstructing land use in Balakhna district, Nizhny Novgorod province, based on the General Land Survey and soil maps. Alyabina et al. (2015) compared socio-economic and soil-geographical information for central European Russia in the late 18th century to calculate average plowing per household, soil fertility, and use efficiency; Kanischev et al. (2020) analyzed settlement trends in Tambov province in the second half of the 18th century; and Beshentsev et al. (2024) reconstructed 20th century environmental change in the central Lake Baikal basin using topographic maps from the Corps of Military Topographers.

Historic and Thematic Maps Integration

This method analyzes land use dynamics by comparing boundaries and areas from General Land Survey plans with modern maps and/or remote sensing data. Classic examples include Ivanova et al. (2023), who assessed land distribution over seven time slices based on General Land Survey plans, Strelbitsky's maps, RKKA topographic maps, and modern General Staff maps, analyzing the spatial location of arable land at different development stages; Shilov and Kozlov (2019), who reconstructed settlement and land use systems during the General Land Survey period and assessed land suitability for plowing on the Valdai Heights; Matasov et al. (2019), who used historical maps, statistics, and satellite imagery to reconstruct landscape change and classify it into six land use regimes in the Ryazan region; and Belyaeva and Popov (2016), who used General Land Survey plans, Schubert's map, Strelbitsky's map, General Staff maps, and Landsat imagery to compare forest cover in Vereysky Uyezd, Moscow region. Comparing multi-temporal historical and thematic maps provides insights into land use dynamics, forest cover change, and landscape transformation (Belevantsev et al.

2019; Kozykin and Nakvasina, 2024). Studying traditional land use history helps understand modern ecosystem structure and function and identify rare ecosystems; for example, Loiko et al. (2024) used historical maps to identify reference soil sites in Northern Priotomye never subjected to plowing.

Thematic Map Analysis

These are comparative studies of land and forest use dynamics based on specialized departmental maps, such as farm soil maps for agricultural land and forest management materials for forests. Examples include Avvakumova (2018), who assessed spatiotemporal soil erosion dynamics in the Republic of Tatarstan based on 1970s soil maps, and Aleinikov et al. (2024), who analyzed 85 years of dynamics of forests with Siberian pine in the Northern Urals by comparing forest management materials.

Satellite Imagery Analysis

These studies analyze land use dynamics using remote sensing data, primarily Landsat satellite imagery processed by expert or automatic interpretation methods. Examples include analyses of agricultural land use changes in Perm Krai from 1986 to 2018 (Belousova and Bryzhko 2021); studies on the waterlogging of arable land in the Tambov region using Landsat and 1960s CORONA archival imagery (Shapovalov et al. 2018); assessments of vegetation fragmentation in the Valdai Lake District since 2009 (Belonovskaya et al. 2015); investigations into afforestation in the Belgorod region based on 1970 CORONA high-resolution data (Chendev et al. 2023); and the use of decision tree algorithms on Landsat imagery to map permanent steppes and their recovery from 1990 to 2018 (Pazur et al. 2021).

Analysis of the study types revealed a predominance of works using satellite imagery and literature reviews as the simplest methods. Studies using thematic maps and reconstructions based on General Land Survey plans were the least common (Fig. 13).

DISCUSSION

General Overview and Limitations of Results

Our review reveals a noticeable decline in publication output after 2018, which may be attributed to factors

such as the COVID-19 pandemic, political situation, shifts in research funding, or the retirement of key researchers. We intentionally focused on domestic Russian journals to capture the breadth of Russian-language scholarship, though this may have excluded some already well-known English-language studies conducted by international teams (Andreeva et al. 2021; Ioffe et al. 2004; Prishchepov et al. 2017). Terminology differences between Russian and Western LSS traditions affect comparability. In landscape ecology, the process of integrating terms has been presented (Bastian et al. 2015; Frolova 2019); while in land system science, this is yet to be done (Meyfroidt et al. 2016). Nonetheless, the corpus of literature analyzed provides a comprehensive overview of historical LSS in Russia. It is also worth noting that significant contributions have been made in monographs and international collaborations (Josephson et al. 2013; Lyuri et al. 2010), though these were beyond the scope of this review.

Regional and Thematic Patterns, Methodological Challenges and Gaps

The spatial distribution of studies is highly uneven, with a strong concentration in European Russia (e.g., Belgorod, Tula, Moscow regions) and minimal coverage of Siberia and the Far East. This bias reflects not only the higher population density in the European part of Russia compared to Siberia and the Far East. This disparity is a result of the historical development of research schools in historical geography and landscape science, often rooted in Soviet-era institutions. Regions with strong academic traditions (e.g., Perm, Irkutsk, Kaliningrad) produced clusters of studies, while vast territories remain under-researched. The correlation between research density and the availability of historical maps (e.g., General Land Survey, Mende maps) is evident: European regions benefit from detailed pre-20th-century materials, whereas Asian Russia relies heavily on satellite imagery and statistical data, limiting temporal depth. Plain landscapes are the subject of 6.5 times more studies than mountain landscapes, despite these two categories representing a relatively balanced share of Russia's territory at approximately 60% and 40%, respectively (Ogureeva et al. 2018). This disparity reflects a strong research bias towards lowland regions, which can probably be attributed to factors such as superior accessibility, more readily available data, and the historical focus on agricultural development. The thematic focus is

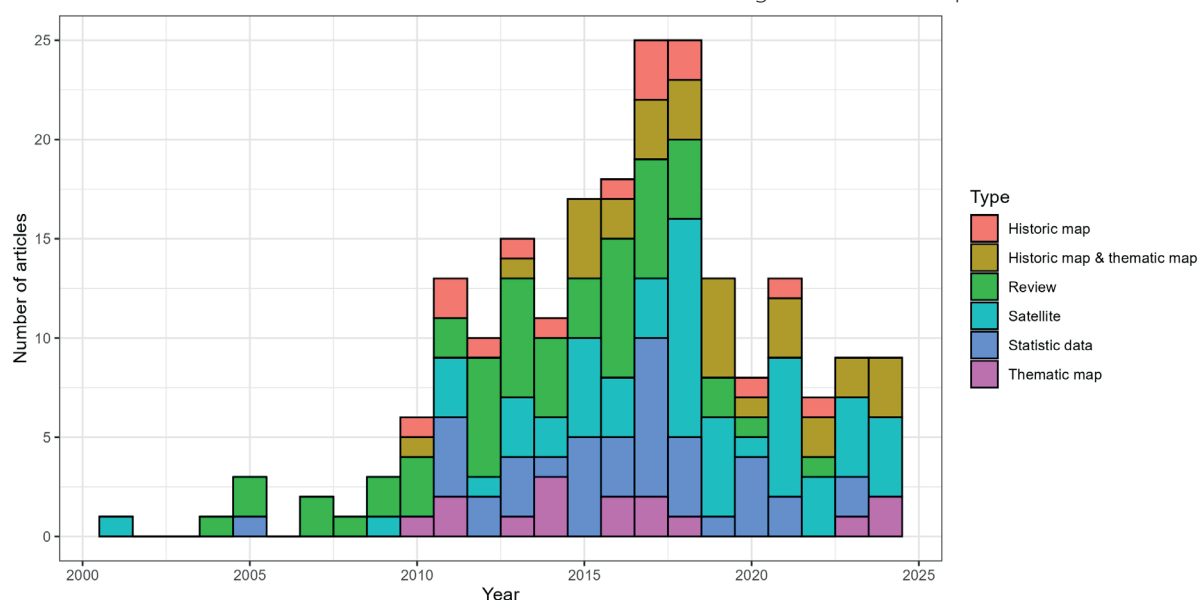


Fig. 13. Temporal distribution of article types

predominantly on the dynamics of agricultural and, to a lesser extent, forested landscapes, primarily in the southern boreal and northern nemoral zones. These regions are characterized by active historical development, which has resulted in pronounced landscape dynamics. In contrast, urban and mountain landscapes are largely overlooked.

We suggest that historical geoinformation science in Russia is currently in its early stages, where research focuses on the simplest objects of natural resource management. These objects—such as plowed or forested areas—possess direct cartographic or spectral signatures and do not require additional modeling. This methodological simplicity is reflected in several other observations. For example, the overwhelming majority of studies are confined to a single site, employ a single spatial resolution, and are limited to a single administrative unit for which a historical map or satellite image is used for comparison. While a significant proportion of long-term studies covering periods exceeding 100 years are promising, most are based on historical surveys or statistical data, which constrains analytical depth.

A clear correlation is evident between the methods used and the spatial and temporal scope of the research. Unfortunately, these methods are often rigidly constrained by historical sources, which can represent a lower limit for historical analysis. The geostatistical methods applied are generally limited to basic area comparisons. Similarly, statistical data analysis methods remain elementary. More advanced techniques—such as spatial modeling, multivariate analysis, machine learning, and interdisciplinary frameworks integrating environmental, historical, and economic data—are almost entirely absent.

It is worth noting a gradual increase in studies that provide quantitative assessments of change as a key conclusion. However, this trend is primarily tied to the growing number of studies using area comparisons based on satellite imagery. Few studies integrate socio-economic drivers or use multi-scale approaches, hindering mechanistic understanding of land change processes. A major constraint to the growth of deep research is the limited accessibility and digitization of historical cartographic materials. Many pre-Soviet and Soviet-era maps remain classified, poorly georeferenced, or fragmented, preventing large-scale integration of GIS analysis methods for them. This forces researchers to rely on remote sensing, which only covers post-1990 trends. Methodologically, geostatistical approaches dominate, but few studies employ advanced modeling, machine learning, or interdisciplinary frameworks that combine ecological, historical, and economic data. There is also a notable lack of open historical mapping platforms or harmonized land cover databases for Russia, which limits reproducibility and comparative analysis.

Positioning Russian LSS within the European and Global Context

Our review shows that the Russian research field contrasts with patterns found in Western and Central Europe. For instance, it differs markedly from the synthesis by Plieninger et al. (2016). While their study found a dense coverage of case studies in EU member states (e.g., Spain, Czech Republic, Italy), our results highlight a significant knowledge gap for Russia, which was notably absent from their analysis along with other Eastern European countries. This disparity underscores Russia's status as a critical blind spot in the pan-European understanding of land system change. The Russian context, characterized by unique

post-Soviet socio-economic transitions, vast scales, and specific biogeographic zones (e.g., boreal forests, steppes, Arctic), offers a distinct and complementary set of drivers and trajectories that are poorly represented in European meta-analyses (Jepsen et al. 2015; Levers et al. 2018). For instance, while land abandonment is a dominant proximate driver across Europe, its causes and consequences in the Russian context – linked to the collapse of state farms and depopulation of remote villages – differ markedly from the market-driven dynamics in Western Europe or the Mediterranean.

Furthermore, the Russian scientific tradition, with its strength in detailed, local-scale historical reconstructions and qualitative case studies, provides a valuable counterbalance to the quantitative, satellite-driven approaches that dominate Western literature. Therefore, integrating Russia's fragmented but deep insights is crucial. It is not merely about filling a geographical gap. It is essential for building a comprehensive LSS theory that accounts for all socio-ecological contexts (Meyfroidt et al. 2013, 2018; Verburg et al. 2013). This integration aligns with the goals of Long-Term Socio-Ecological Research, which emphasizes the need for place-based, long-term data to understand complex system dynamics (Angelstam et al. 2019; Singh et al. 2010). Our synthesis of Russian studies provides a crucial foundational step towards creating such a platform for Russia, enabling future cross-site comparisons and enriching global models like HYDE (Klein Goldewijk et al. 2011) with much-needed data from the world's largest country. Ultimately, bridging this divide is paramount for addressing transboundary sustainability challenges, from carbon sequestration in boreal forests to biodiversity conservation across Eurasia.

CONCLUSION

Studying land-use dynamics in Russia is critically important due to the country's significant global influence. Its extensive boreal forests act as a major carbon sink, while the thawing of permafrost threatens to release vast quantities of greenhouse gases. Furthermore, Russian policies on agriculture and resource extraction have a direct impact on global food and energy security. Ultimately, these changes in land use both reflect and shape pivotal economic, environmental, and geopolitical trends that extend far beyond its borders. The systematic review uncovers pronounced geographical and thematic disparities in Russian LSS research. Empirical findings demonstrate a strong spatial bias, with the overwhelming majority of case studies concentrated in the European part of the country, such as the Belgorod and Moscow regions, while vast areas of Siberia, the Far East, and the Arctic remain critically understudied. Thematically, research is dominated by investigations into agricultural land abandonment and forest dynamics, whereas urban landscapes receive minimal scholarly attention. This uneven coverage limits a comprehensive understanding of land-change processes across Russia's diverse socio-ecological systems. Methodologically, the researches are characterized by significant constraints. A substantial majority of studies (74.2%) are confined to a single spatial scale and a single study site, predominantly using administrative boundaries rather than biogeographical units. Furthermore, 74% of the reviewed publications do not systematically analyze the causal drivers behind the observed landscape changes. Compounding these issues is a persistent linguistic and visibility gap, with 82% of studies published only in Russian and a significant portion not indexed in international

databases, which severely limits the global integration of this research.

This paper is the first in a series of review articles that aim to foster knowledge exchange among researchers – including ecologists, geographers, historians, economists, and climatologists – as well as practitioners involved in the study and management of Russian lands. To advance LSS in Russia, we recommend:

- Expanding research into understudied regions, such as Siberia, the Far East, and the Arctic.
- Integrating multi-source historical and modern data through GIS and machine learning techniques.

- Fostering interdisciplinary collaborations across fields such as ecology, history, economics, and archaeology.

- Developing open-access geodatabases and producing regional historical land-cover reconstructions.

- Enhancing international engagement by disseminating findings in both English and Russian and promoting collaborative projects.

These efforts would not only increase the visibility of research from Russia but also contribute significantly to the global understanding of land-system dynamics within its unique socio-ecological contexts. ■

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THE CHANGING CLIMATE OF KIELCE: INSIGHTS FROM EXTENDED METEOROLOGICAL ANALYSES

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ABSTRACT. The study examined air temperature and monthly precipitation totals recorded between 1966 and 2023 at the hydrological and meteorological station of the Institute of Meteorology and Water Management (IMWM) in Kielce-Suków and the Copernicus Climate Change Service Climate Data Store (CDS). Based on these data, thermal and precipitation classifications were developed, supplemented by an extended assessment of snow cover duration in the Kielce region.

The results confirm a clear warming trend, reflected in an increasing number of warmer-than-average months and a decline in colder ones. The mean annual temperature has risen by approximately 0.03°C per year (0.33°C per decade), amounting to 1.62°C over the entire study period. Projections suggest an additional increase of approximately 1°C by 2030.

Snow cover conditions exhibited substantial variability. The mean number of days with snow cover (≥ 1 cm) was 63, ranging from 7 days in 2020 to 114 days in 1969, indicating a decline in recent decades. Average winter snow depth (December–March) was 4.84 cm, with extreme values recorded in 2020 (0.07 cm) and 1970 (23.4 cm). Maximum annual snow depth varied between 4 cm (2020) and 55 cm (1970). The mean duration of persistent snow cover (≥ 30 days) was 45 days, with a maximum of 88 days in 2006.

Precipitation patterns did not show a consistent long-term trend comparable to temperature. While summer months (June–August) still receive the highest totals, their temporal distribution is shifting. Some months (e.g., July, September) exhibit decreasing precipitation, whereas others (e.g., August, December) show increasing or no clear tendencies. The observed annual and seasonal variability is likely to intensify under ongoing climate change.

These findings underscore important implications for local ecosystems, agriculture, and water resource management, highlighting the need for adaptive strategies in the Świętokrzyskie region.

KEYWORDS: climate change, Kielce, air temperature, snow cover, precipitation

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INTRODUCTION

In urban areas, rising air temperatures are intensified by the urban heat island effect, driven by the dominance of paved and asphalted surfaces and the limited presence of dense vegetation. These materials absorb and retain heat, thereby increasing urban air temperatures (EPA 2025). Impermeable surfaces also restrict natural rainfall infiltration, which enhances the risk of flash floods during intense precipitation events (Pappalardo et al. 2023). Reduced greenery and permeable ground accelerate surface runoff into drainage systems that often lack sufficient capacity, exacerbating flood hazards and placing additional pressure on urban ecosystems (Fahy et al. 2019; Sohn et al. 2020; Szeląg et al. 2024).

Recent research increasingly highlights regional manifestations of global climatic processes. Although numerous studies address climate variability in Poland, long-term assessments specific to the Świętokrzyskie region remain limited. This study seeks to fill this gap by analyzing nearly six decades of air temperature, precipitation, and snow cover data from the Kielce-Suków station.

The transitional position of the Kielce region between lowland and upland areas makes it a valuable case study for understanding climate variability in Central Europe. Contemporary climate research focuses strongly on identifying trends and extremes in air temperature and precipitation, which are key determinants of environmental conditions and the functioning of natural systems. These changes are evident at both global and regional scales, influencing landscapes, hydrology, agriculture, and natural as well as urban ecosystems (IPCC 2023; Malhi et al. 2020).

In Poland, as in other parts of Central Europe, systematic increases in mean annual temperature and shifts in precipitation patterns have been documented in numerous climatological studies (Miętus et al. 2022; Wibig and Jakusik 2012). The Świętokrzyskie region, located in southeastern Poland, is particularly suitable for such analyses due to its varied terrain, diverse land use structure, and the presence of local climatic factors (Twardosz and Kossowska-Cezak 2016). The long-term operation of the IMWM meteorological station in Kielce-Suków provides a robust dataset enabling the evaluation of climatic changes in this area.

The examination of air temperature and precipitation from this station fits within broader research on the climatic regionalization of Poland (Lorenc 2000; Piotrowicz 2003), assessments of the frequency and intensity of extreme events (Kundzewicz et al. 2016), and studies on the impacts of climate change on water management and ecosystems (Kozłowska-Szczęśna et al. 1997; Ziernicka-Wojtaszek 2019). Climatic changes affect water balance and agroclimatic conditions, as well as the dynamics of natural and cultivated plant communities (Podgórska and Szwed 2017; Jarzyna et al. 2017), modifying the length of the growing season and increasing drought risk (Szwed et al. 2010; Chmielewski and Rotzer 2001).

The aim of this article is to characterize changes in air temperature and precipitation in the Świętokrzyskie region based on data from the IMWM Kielce-Suków station for the years 1966–2023. The analysis uses long-term time series to assess seasonal and annual variability of meteorological parameters, identify trends, and determine potential phenological shifts. Particular attention is given to the possible regional and environmental implications of the observed changes.

MATERIALS AND METHODS

Research area

The IMWM meteorological station in Kielce-Suków is located southeast of the Kielce city center, in the village of Suków, within the Świętokrzyskie Voivodeship. The station lies at an elevation of approximately 260 m a.s.l. on the edge of a loess upland, in an open area that ensures the proper exposure of instruments in accordance with World Meteorological Organization (WMO) standards. This setting provides high representativeness for the climatic

conditions of the Świętokrzyskie region, particularly for suburban and agricultural landscapes (Fig. 1). According to the physical-geographical regionalization of Poland by Jerzy Kondracki (2002), the Kielce-Suków station is situated within the Polish Uplands province, the Małopolska Upland subprovince, and the Kielce Upland macroregion, specifically in the Świętokrzyskie Mountains mesoregion. This area is characterized by a diverse landform structure dominated by hills, slopes, and river valleys. The region also exhibits substantial geological variability, with sedimentary rocks—primarily limestones, marls, sandstones, and Paleozoic shales—prevailing. The presence of complex tectonic structures further contributes to local microclimatic differentiation.

The climate of the Świętokrzyskie region, including the area surrounding Kielce, is shaped by both its geographical setting and morphological features. It reflects characteristics of a temperate transitional climate, influenced by oceanic and continental air masses. Annual precipitation generally ranges from 600 to 750 mm, and the mean annual air temperature is approximately 7–8°C, although an upward trend has been observed in recent decades (Lorenc 2005; Dubicka et al. 2020). The Kielce Upland tends to be slightly cooler than the adjacent lowlands, which is associated with its elevation, forest cover, and differences in slope exposure.

The significance of the Kielce-Suków station as an observational site stems from its location in a transitional zone between lowland and upland areas, as well as from its extensive measurement record, which enables long-term climate analyses. Data collected at this station are widely used in meteorological and climatological research and have practical applications in hydrology and agriculture (Farat et al. 2010; Ziernicka-Wojtaszek 2019).

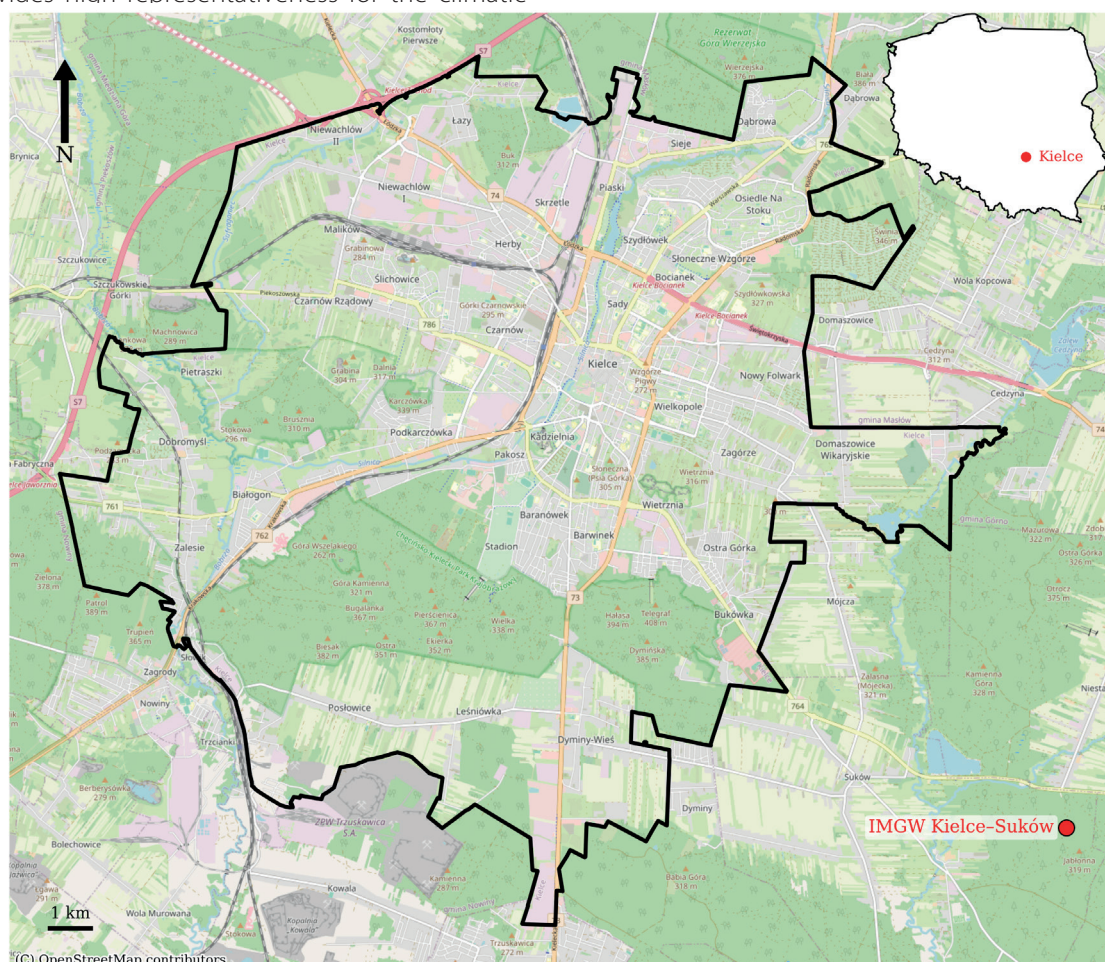


Fig. 1. Location of the IMWM Kielce-Suków station (based on OpenStreetMap)

Methods

The analysis of climatic conditions in the Kielce region was based on measurement data from the IMWM Kielce-Suków station, covering the multi-year period 1966–2024. Three fundamental meteorological elements were examined: air temperature, total precipitation, and the occurrence and depth of snow cover. To evaluate thermal conditions, the classification proposed by Lorenc and Bogucka (1996) was applied, enabling each calendar month to be assigned to one of eleven thermal classes according to deviations of monthly temperature from the mean value in the reference period. The baseline period was defined as the multi-year interval 1966–2023. This classification provides a systematic framework for assessing thermal anomalies on both monthly and seasonal scales (Table 1).

For borderline values, rounding to one decimal place was applied. The classification allows for the identification of thermal trends and the detection of extreme months, such as cold spells or heatwaves.

Annual and monthly precipitation totals were classified using a statistical approach based on percentiles derived from the distribution of values for the multi-year period 1966–2023. Five humidity classes were adopted, following methodologies commonly used in studies on the climate of Poland (Dubicka et al. 2020; Degirmendžić et al. 2004) (Table 2).

This classification allows for determining the frequency of occurrence of abnormally dry or wet years or months, which is important in the analysis of drought or flood risks.

Snow cover was analyzed based on daily observations of snow depth (in cm) and the number of days with snow cover recorded at the Kielce-Suków station. According to

the guidelines of hydrometeorological stations, snow cover is recorded when the ground area surrounding the station is covered by snow over more than 50% of its surface. The snow cover is considered persistent if it remains for at least one month, with interruptions not exceeding three consecutive days. The analysis included the number of days per year with snow cover ≥ 1 cm, the average snow depth during the winter season (December–March), the maximum annual snow depth, and the dates of the onset and disappearance of persistent snow cover. Additionally, to identify seasonal changes, the average dates of the first and last snow cover in the season, as well as the duration of snow cover (both continuity and total number of days) were determined.

The data were analyzed with respect to long-term trends, inter-seasonal variability, and relationships with thermal and precipitation conditions. Basic descriptive statistics and trend analysis (linear regression) were applied for selected climate parameters.

The detection of heatwaves in this study follows the approach outlined by Perkins and Alexander (2013), which defines heatwaves as periods of at least three consecutive days (or months in the aggregated data) with temperatures exceeding a specific threshold based on historical climatology. Thresholds are typically set using percentile-based metrics (e.g., the 90th or 95th percentile of daily or monthly temperatures) to capture extreme thermal events relative to local climate variability.

Droughts are identified by consecutive months with precipitation below a critical percentile threshold (commonly the 25th percentile), indicating prolonged dry conditions. This percentile-based method ensures that drought definitions are sensitive to regional climate norms and variability.

Table 1. Thermal classification according to Lorenc and Bogucka (1996)

Thermal category	Condition of annual temperature relative to mean and standard deviation (SD)
Extremely warm	$T_{\text{annual}} > T_{\text{mean}} + 2.5 \text{ SD}$
Anomalously warm	$T_{\text{mean}} + 2.0 \text{ SD} < T_{\text{annual}} \leq T_{\text{mean}} + 2.5 \text{ SD}$
Very warm	$T_{\text{mean}} + 1.5 \text{ SD} < T_{\text{annual}} \leq T_{\text{mean}} + 2.0 \text{ SD}$
Warm	$T_{\text{mean}} + 1.0 \text{ SD} < T_{\text{annual}} \leq T_{\text{mean}} + 1.5 \text{ SD}$
Slightly warm	$T_{\text{mean}} + 0.5 \text{ SD} < T_{\text{annual}} \leq T_{\text{mean}} + 1.0 \text{ SD}$
Normal	$T_{\text{mean}} - 0.5 \text{ SD} \leq T_{\text{annual}} \leq T_{\text{mean}} + 0.5 \text{ SD}$
Slightly cold	$T_{\text{mean}} - 1.0 \text{ SD} \leq T_{\text{annual}} < T_{\text{mean}} - 0.5 \text{ SD}$
Cold	$T_{\text{mean}} - 1.5 \text{ SD} \leq T_{\text{annual}} < T_{\text{mean}} - 1.0 \text{ SD}$
Very cold	$T_{\text{mean}} - 2.0 \text{ SD} \leq T_{\text{annual}} < T_{\text{mean}} - 1.5 \text{ SD}$
Anomalously cold	$T_{\text{mean}} - 2.5 \text{ SD} \leq T_{\text{annual}} < T_{\text{mean}} - 2.0 \text{ SD}$
Extremely cold	$T_{\text{annual}} < T_{\text{mean}} - 2.5 \text{ SD}$

Table 2. Precipitation classification

Humidity category	Range (percentiles)
Very dry	$\leq 10^{\text{th}}$ percentile
Dry	11 th –25 th percentile
Normal	26 th –75 th percentile
Wet	76 th –90 th percentile
Very wet	$\geq 91^{\text{st}}$ percentile

This combined methodology provides a robust framework to analyze the frequency, duration, and intensity of heatwaves and droughts over time, facilitating the assessment of climate extremes and their potential impacts.

Long-term trends were evaluated using linear regression, with the slope parameter indicating the rate of change per year. The statistical significance of trends was assessed using Student's t-test for regression slopes and Kendall's tau test for monotonic trends, with p-values < 0.05 considered significant. All computations and visualizations were performed in R version 4.3.1 (R Core Team, 2023) using the *trend* and *ggplot2* packages.

To complement the station data, ERA5 reanalysis data were downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (Hersbach et al. 2020), covering the period 1981–2023. ERA5 provides global estimates of meteorological variables at a horizontal resolution of approximately 31 km, allowing for comparison between local observations and large-scale reanalysis products. This comparison was performed to evaluate how well global datasets reproduce regional climate patterns and to assess the consistency of observed temperature and precipitation trends.

RESULTS

Based on the conducted research and analysis of meteorological data for the period 1966–2023, it was found that the average annual air temperatures exhibit a clear upward trend (Fig. 2). At the beginning of the observation period (1960s), the average temperature values ranged around 6–8°C, whereas in the last two decades, the average annual temperatures have consistently exceeded 8°C, reaching local maxima in 2018 (9.38°C), 2019 (9.73°C), and 2023 (9.58°C). This phenomenon indicates progressive climate warming in the Kielce region, consistent with global climate trends observed worldwide.

Based on the analysis of monthly average air temperature values from 1966 to 2023, conducted according to the thermal classification by Lorenc and Bogucka (1996),

a detailed distribution of the frequency of occurrence of individual thermal classes was obtained (Fig. 3). This summary reflects the scale of thermal variability in the region and enables the identification of long-term climatic trends.

During the analyzed 58-year period (1966–2023; 696 months), the largest number of months was classified as thermally normal — a total of 275 months (39.5%). The next most frequent categories were slightly warm months (110 months, 15.8%) and slightly cold months (96 months, 13.8%), confirming the predominance of moderate temperature conditions characteristic of Poland's transitional climate.

Warm and very warm months occurred a total of 96 times (13.8%), while warm anomalies (anomalously and extremely warm months) were recorded in 11 cases (1.6%). In contrast, cold and very cold months appeared 88 times (12.6%), and cold anomalies (anomalously and extremely cold months) occurred in 20 months (2.9%).

On an annual scale, most years were also classified as thermally normal (22 years). Slightly cold and slightly warm years were recorded 9 and 8 times, respectively, while warm and very warm years occurred 5 and 4 times. The coldest categories — cold and very cold years — appeared 3 and 4 times, respectively, whereas thermal anomalies (anomalously cold and anomalously warm years) were rare, occurring only in three cases in total (two anomalously cold and one anomalously warm year).

Basic statistics were calculated for N-month periods:

- **slope** — the average annual change in the number of months within a given thermal class; a positive slope indicates an increasing number of months in that class, while a negative slope indicates a decreasing number of months;
- **p-value** (statistical significance test of the trend); $p < 0.05$ means the trend is statistically significant, $p \geq 0.05$ means there is insufficient evidence to confirm the trend;
- **R²** (coefficient of determination) indicates how well the linear model explains data variability (values range from 0 to 1); values close to 1 indicate a good fit, and values close to 0 indicate a poor fit.

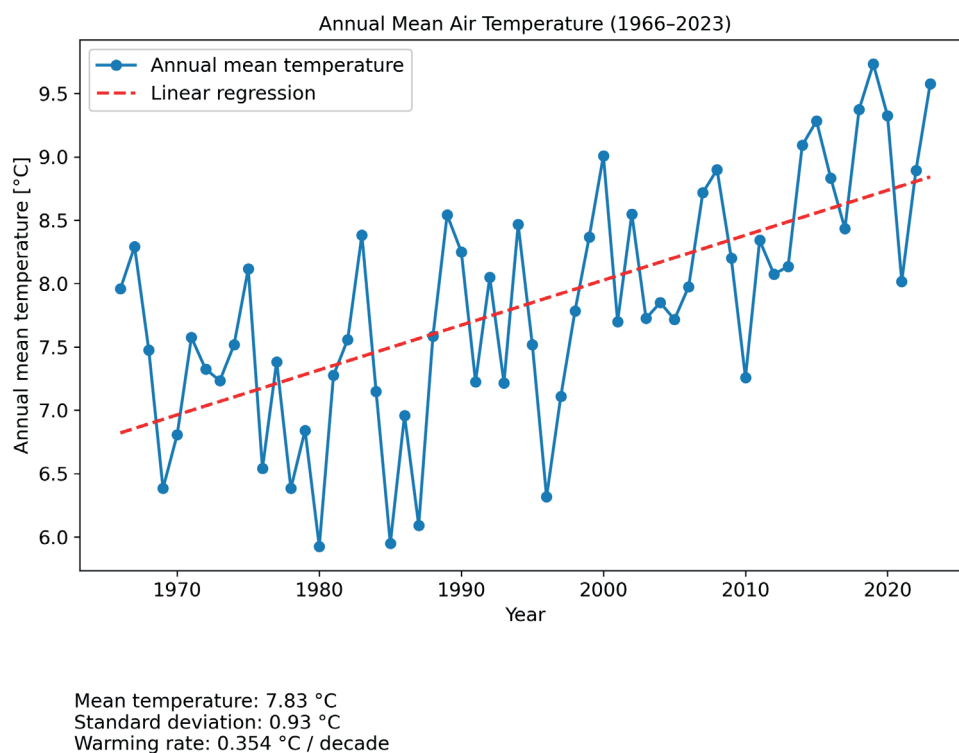


Fig. 2. Changes in the average annual air temperature values

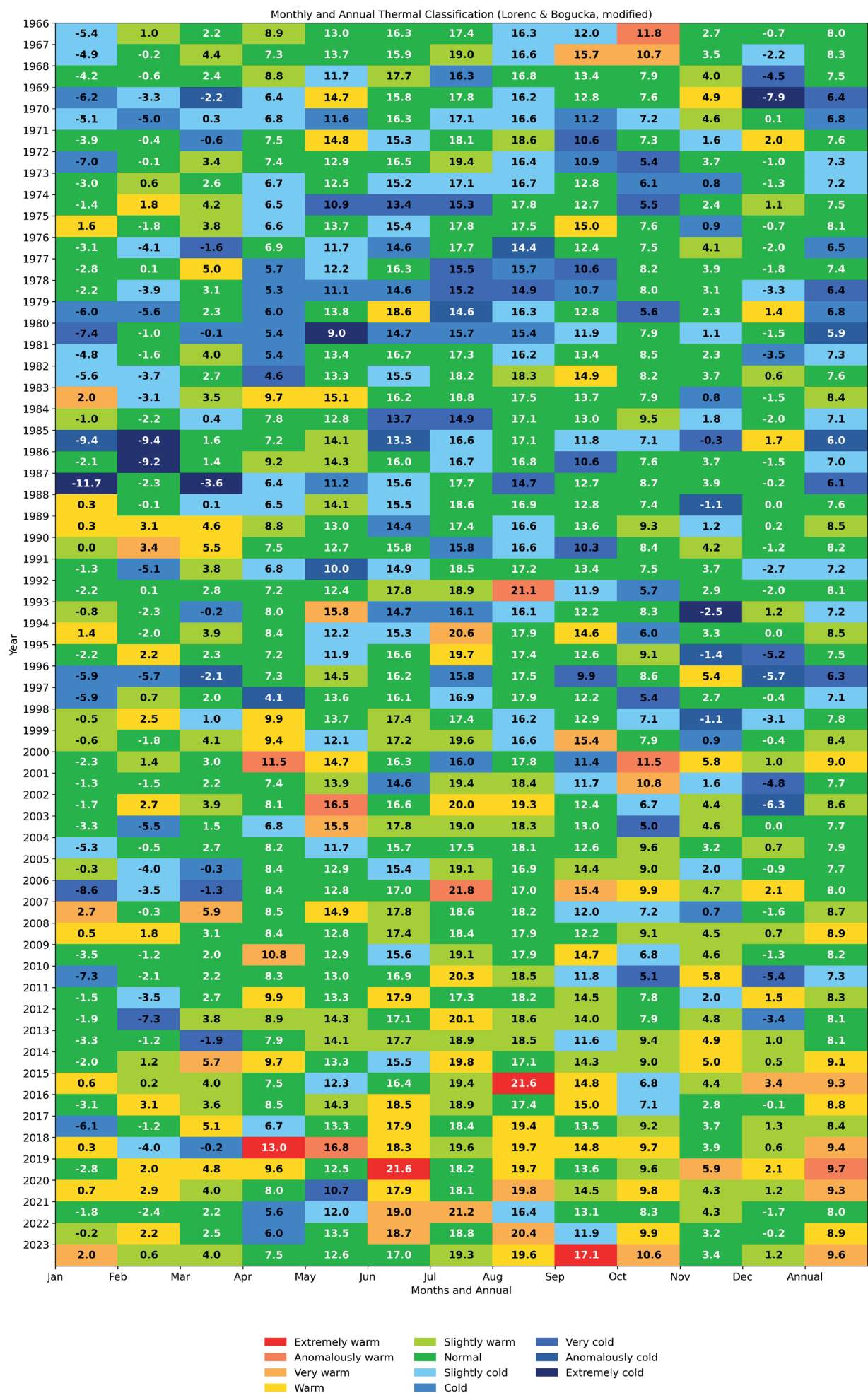


Fig. 3. Thermal classification according to Lorenc and Bogucka (1996)

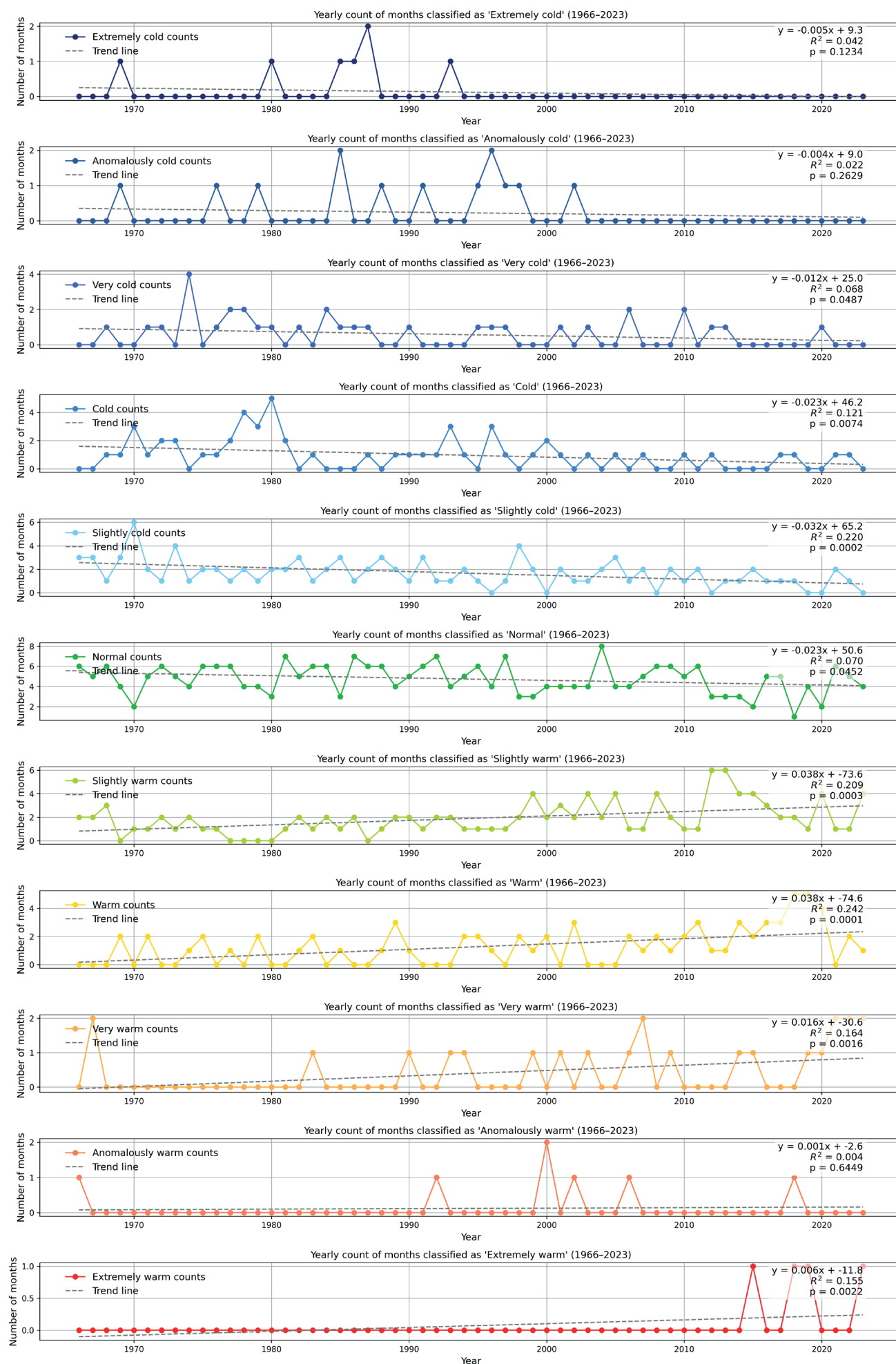


Fig. 4. Changes in the occurrence of individual thermal classes over the studied multi-year period

Based on the analysis of trends in individual thermal classes, a clear shift in the frequency of occurrence of months with different thermal characteristics was observed throughout the study period (Fig. 4, Table 3). Within the colder classes (from “very cold” to “slightly cold”), statistically significant decreasing trends were found, indicating a reduction in the frequency of cold months. The strongest negative trend occurred in the “slightly cold” class (slope = -0.032 , $p = 0.0002$, $R^2 = 0.22$), meaning that such months have become increasingly rare over time.

In contrast, the warm classes (“slightly warm,” “warm,” “very warm,” and “extremely warm”) exhibit statistically significant positive trends, reflecting an increase in the frequency of warmer-than-normal months. The strongest positive trend was observed in the “warm” class (slope = 0.038 , $p = 0.0001$, $R^2 = 0.242$), while a similarly significant but slightly weaker trend was found for the “slightly warm” class.

The extreme classes (“anomalously cold” and “anomalously warm”) show no significant trends, suggesting that despite the overall warming tendency, the occurrence of thermally extreme months remains irregular and variable.

Overall, the results clearly indicate a systematic warming of the climate in the analyzed period, manifested by a decrease in the frequency of cold months and an increase in the occurrence of warm months.

Analysis of annual precipitation totals revealed significant variability between individual years, with values ranging widely from 439 mm (in 1982) to nearly 1000 mm (in 1966). Unlike temperatures, the precipitation totals do not show a clear increasing or decreasing trend over the studied period. Average annual precipitation generally remains within the range of 500 to 750 mm, which is characteristic of a temperate climate, where precipitation dynamics are strongly influenced by variable atmospheric factors and local meteorological conditions (Fig. 5).

The obtained results indicate that, despite the observed global warming trend, precipitation in the Kielce region does not show a similar tendency in quantitative changes over the studied period. The limited predictability of annual precipitation totals highlights the need for further detailed studies considering seasonal and long-term fluctuations and their impact on local ecosystems and water management.

Table 3. Characteristics of individual thermal classes

Thermal class	N	Slope	p-value	R ²	Interpretation
Extremely cold	7	-0.005	0.1234	0.042	No significant trend
Anomalously cold	13	-0.004	0.2629	0.022	No significant trend
Very cold	33	-0.012	0.0487	0.068	Significant but weak decreasing trend, poor fit
Cold	55	-0.023	0.0074	0.121	Significant decreasing trend, moderate fit
Slightly cold	96	-0.032	0.0002	0.22	Significant decreasing trend, moderate fit
Normal	275	-0.023	0.0452	0.07	Significant decreasing trend, poor fit
Slightly warm	110	0.038	0.0003	0.209	Significant increasing trend, moderate fit
Warm	73	0.038	0.0001	0.242	Significant increasing trend, moderate fit
Very warm	23	0.016	0.0016	0.164	Significant but weak increasing trend, moderate fit
Anomalously warm	7	0.001	0.6449	0.004	No significant trend
Extremely warm	4	0.006	0.0022	0.155	Significant but weak increasing trend, moderate fit

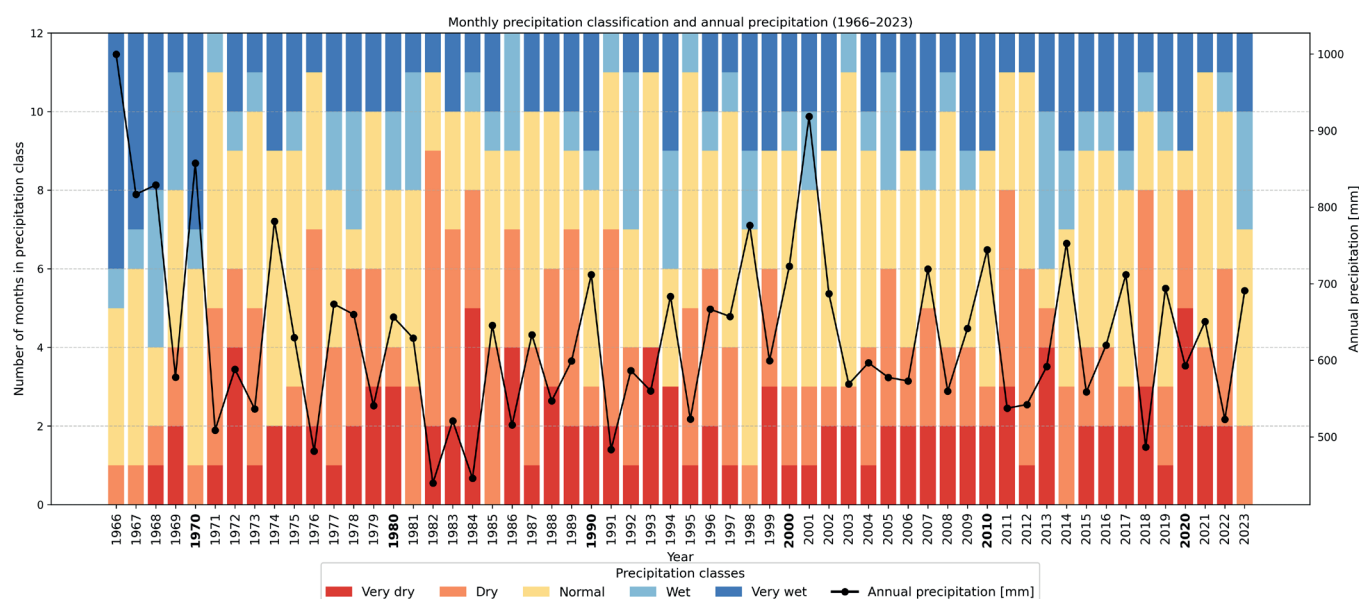


Fig. 5. Precipitation classification during the studied period

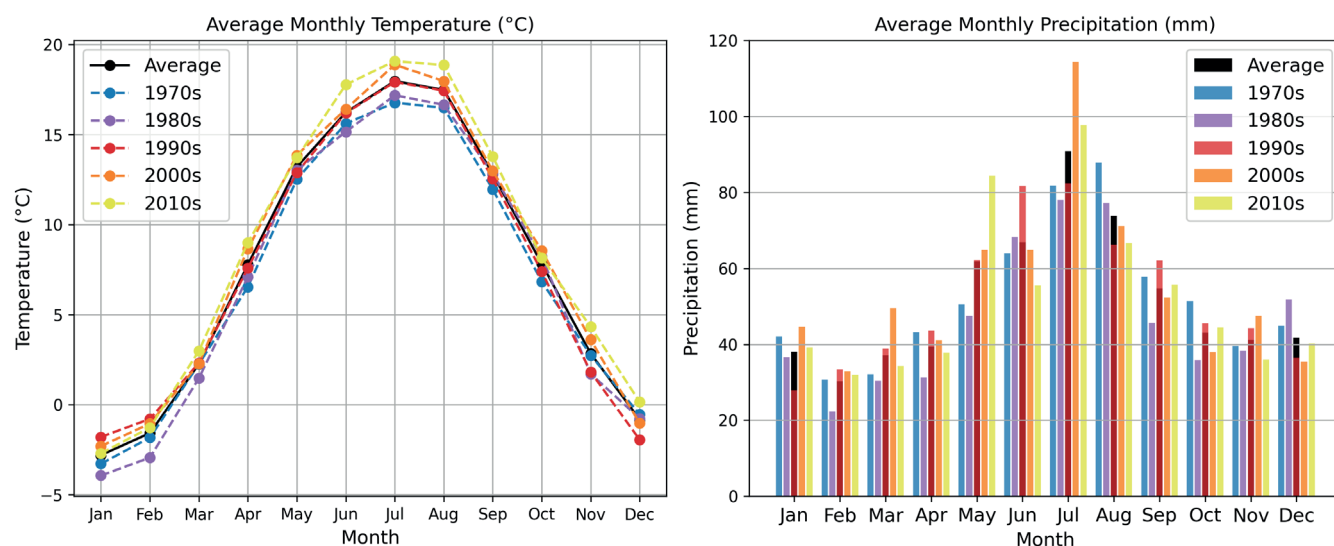


Fig. 6. Trends of temperature and precipitation totals in individual decades of the multi-year period

Based on the course of the average monthly air temperature and precipitation totals (Fig. 6), the following features can be observed:

- The greatest temperature increase occurred in January (+5.32°C), August (+2.57°C), and March (+2.08°C).
- Winter warming is evident — temperatures shifted from distinctly negative values in the 1960s to positive values by 2020.
- Significant summer warming.
- Spring and autumn show smaller changes, sometimes even stability or slight cooling (April, May).
- No clear trend in precipitation — rainfall does not show a systematic increase or decrease as distinct as temperature.
- High variability between decades — for example, June and July in 1960 had very high precipitation, which later significantly decreased.

• Summer precipitation (June–August) exhibits the greatest differences between years, which may indicate increasing irregularity (e.g., storms, droughts). A particularly dynamic pattern is observed in the number of days with snow cover over the analyzed period, 1966–2024 (Fig. 7).

The analysis indicates a significant and consistent decline in the number of days with snow cover during

the study period. Although the linear trend does not account for all variability in the data—which is expected under climatic conditions influenced by multiple factors—statistical tests confirm that the decrease in snow cover days is a real and robust phenomenon ($\tau = -0.306$). On average, the number of days with snow cover decreases by approximately 0.61 days per year. From the beginning to the end of the studied period, the number of snow-cover days has declined by over 78%.

The long-term analysis of snow cover data from 1966 to 2024 reveals substantial interannual variability and a clear downward tendency in both snow persistence and depth. The number of days with snow cover (≥ 1 cm) varied considerably between years, ranging from over 100 days in particularly snowy winters (e.g., 1969, 1970, 1996, 2006, 2010) to fewer than 10 days in exceptionally mild winters such as 2020 (Table 4).

The average snow depth during the winter season (December–March) also shows a marked decline over the study period. In the late 1960s and early 1970s, average values frequently exceeded 5–10 cm, with extreme seasons such as 1970 and 2006 reaching 15–20 cm. In contrast, since the 2010s, the mean snow depth has often remained below 3 cm, reflecting milder winter conditions and shorter snow accumulation periods.

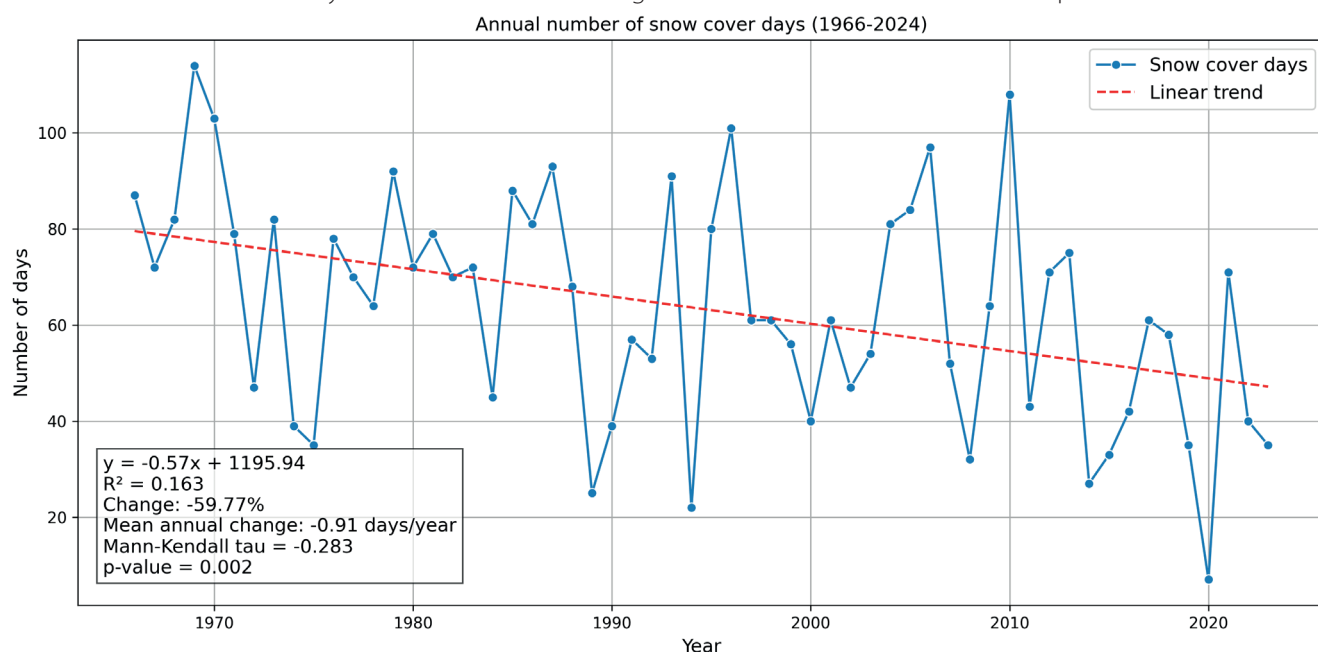


Fig. 7. Number of days with snow cover in individual years over the period 1966–2024

Table 4. Statistical characteristics and long-term trends of snow cover parameters (1966–2024)

Parameter	Mean	Min (Year)	Max (Year)	Std. Dev.	Trend per decade
Days with snow cover (≥ 1 cm)	62.73	7 (2020)	114 (1969)	24.05	-6.05
Average snow depth in winter (Dec–Mar)	4.84	0.07 (2020)	23.4 (1970)	4.5	-0.52
Maximum annual snow depth	20.36	4.0 (2020)	55.0 (1970)	9.35	-0.93
Persistent snow cover duration (≥ 30 days)	25.75	0.0 (1971)	96.0 (1969)	29.87	-5.13

The mean annual number of snow-cover days was approximately 63, showing high interannual variability (ranging from 7 days in 2020 to 114 days in 1969). The trend analysis confirms a consistent decrease in both snow duration and depth, with the decline being particularly evident after the year 2000.

The average winter snow depth was 4.84 cm, and the maximum annual snow depth reached an average of 20.36 cm, with both parameters exhibiting a marked reduction over time—especially in the most recent decades. Periods of persistent snow cover (lasting at least 30 consecutive days) were regularly observed from the 1960s through the early 1990s, often extending from early January to late February or even into March (e.g., 1970, 1987, 1996, 2006, 2010). In recent decades, such prolonged snow periods have become rare or completely absent, indicating a fundamental shift in the local snow regime.

The heatmap reveals clear seasonal patterns in the temperature trends associated with different precipitation classes (Fig. 8). The strongest and most coherent changes occur during the summer (July–September) and late-autumn (November) months, whereas trends in the winter and early-spring period remain weak or statistically insignificant. Most precipitation classes—particularly wet and moderately dry months—exhibit predominantly positive slopes, indicating a systematic warming during the second half of the year. Notable contrasts are evident among the classes: for example, in the “very dry” category, July shows a strong negative trend, while November displays an exceptionally pronounced positive trend.

This variability suggests that the temperature response to precipitation regime is nonlinear and likely driven by interactions between atmospheric circulation, cloud cover, and local water-energy balance.

Overall, the results highlight an intensifying warming signal in late summer and autumn, accompanied by substantial variability across extreme precipitation conditions.

The analysis of heatwaves and drought occurrences across decades from the 1970s to the present reveals clear climate changes in the Kielce region (Fig. 9). In terms of heatwaves, none were recorded in the 1970s, indicating that extremely warm years were very rare or absent during this period. The first heatwaves appeared in the 1980s and 1990s, but they were still relatively infrequent, occurring in about 20% of the years. In the 2000s, there was a noticeable increase in heatwave frequency, reaching 40% of years. The most significant rise occurred in the last decade—the 2010s—when heatwaves were present in 60–70% of the years, clearly signaling a strong warming trend and a growing number of extreme heat events in the region.

Regarding droughts, their frequency in the 1970s was relatively high, ranging from 25% to 50% of years, indicating notable precipitation deficits already during these decades (Fig. 9). The peak drought frequency occurred in the 1980s and 1990s, affecting 50–70% of the years, which reflects very frequent dry conditions. However, in the 2000s, drought frequency sharply declined to about 10%, possibly due to climatic variability or increased rainfall during that period.

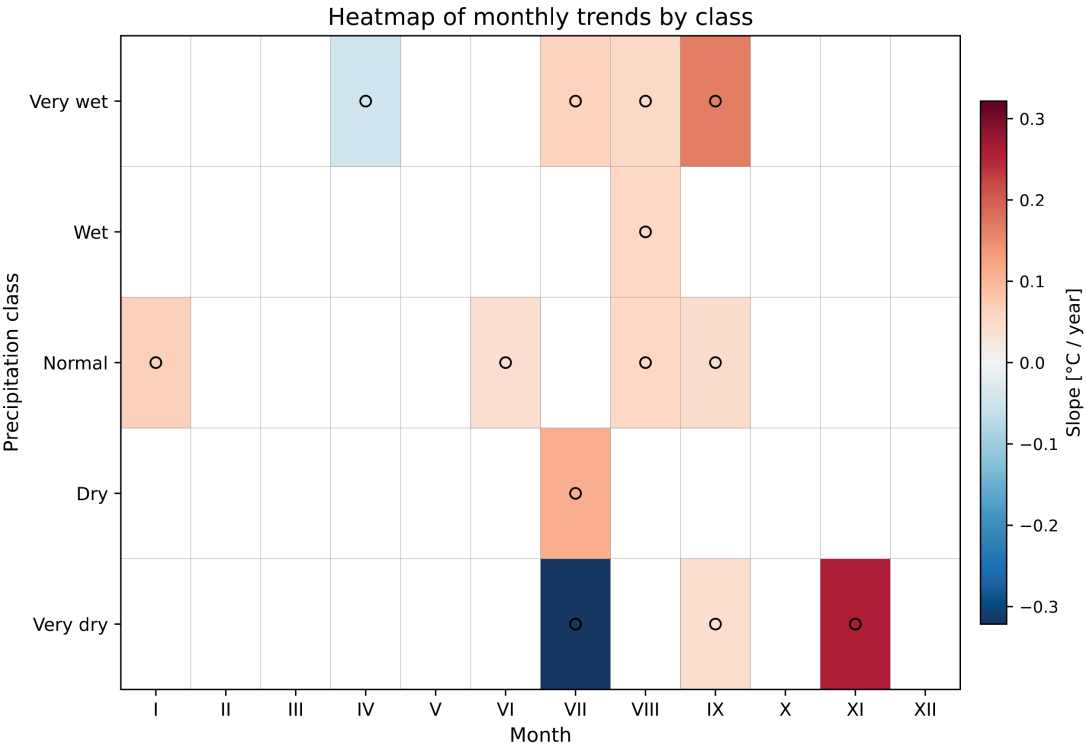


Fig. 8. Heatmap: the circle marker inside selected grid cells indicates that the trend is statistically significant at the adopted significance level (typically $p < 0.05$)

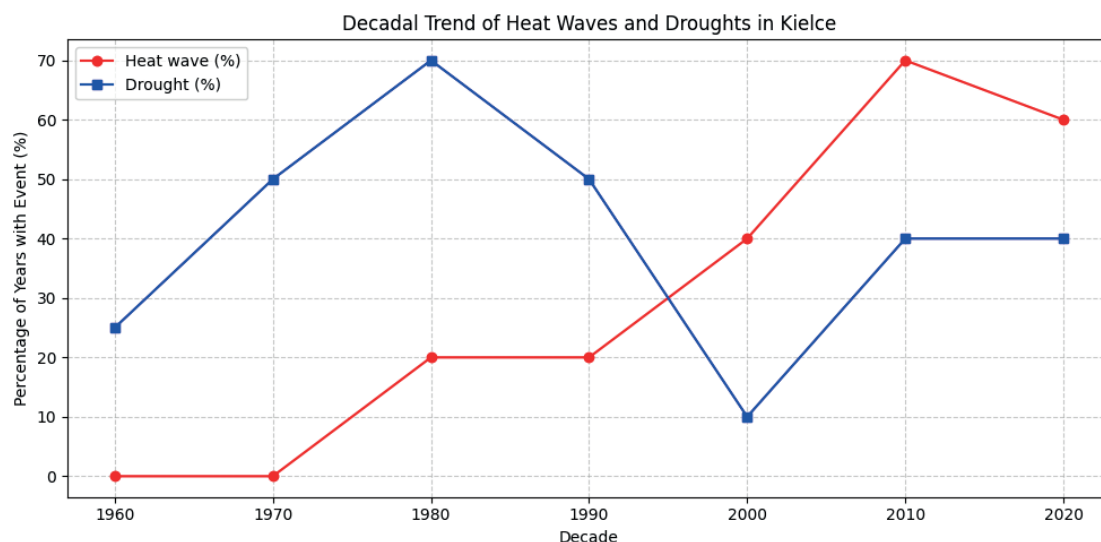


Fig. 9. Occurrence of heatwaves and droughts in Kielce (1960–2020)

Comparing both phenomena, the early decade (1970s) experienced low heatwave frequency but relatively frequent droughts. Since the 1980s, there has been a marked increase in heatwaves, especially pronounced in the last two decades. Drought frequency has been more variable, peaking in the 1980s, decreasing in the 2000s, and increasing again in recent years. The 2010s are characterized by frequent co-occurrence of heatwaves and droughts, signaling growing climatic stress on agriculture, ecosystems, and public health.

The applied forecasting approaches — the linear trend model and the ARIMA model — exhibit a high degree of consistency in projecting the mean annual air temperature for the year 2030 (Fig. 10). The obtained estimates are 9.14°C for the linear model and 9.16°C for the ARIMA model. This minimal difference indicates that the temperature dynamics in the analyzed time series are predominantly governed by a stable and unidirectional long-term warming trend.

The ARIMA model, which incorporates the autoregressive structure and differencing components in addition to the trend, yields a slightly higher forecast. This can be attributed to its ability to account for short-term fluctuations and the memory of the process,

potentially amplifying the upward signal to a small extent. Nevertheless, the difference of approximately 0.02°C is statistically negligible given the length of the series and the inherent forecast uncertainty.

The convergence of both models strengthens the reliability of the estimated warming rate in the study area. The projected values clearly suggest a continuation of the long-term upward temperature trend through 2030, aligning with broader observations of climatic warming at both national and global scales.

The Mann-Kendall test results indicate a clear increasing trend in daily mean temperature at the Kielce station (IMGW), with a Sen slope of approximately 0.464 °C per decade. ERA5 reanalysis data over the same period also show a statistically significant increasing temperature trend, with a slightly smaller Sen slope of 0.428 °C per decade. These results suggest that ERA5 captures the general warming signal observed in station measurements, though the station data indicate a marginally stronger warming.

For precipitation, the trends are less pronounced. The IMGW data show a weak decreasing trend, while ERA5 indicates no significant trend. The Sen slopes are effectively zero for both datasets, confirming that annual precipitation

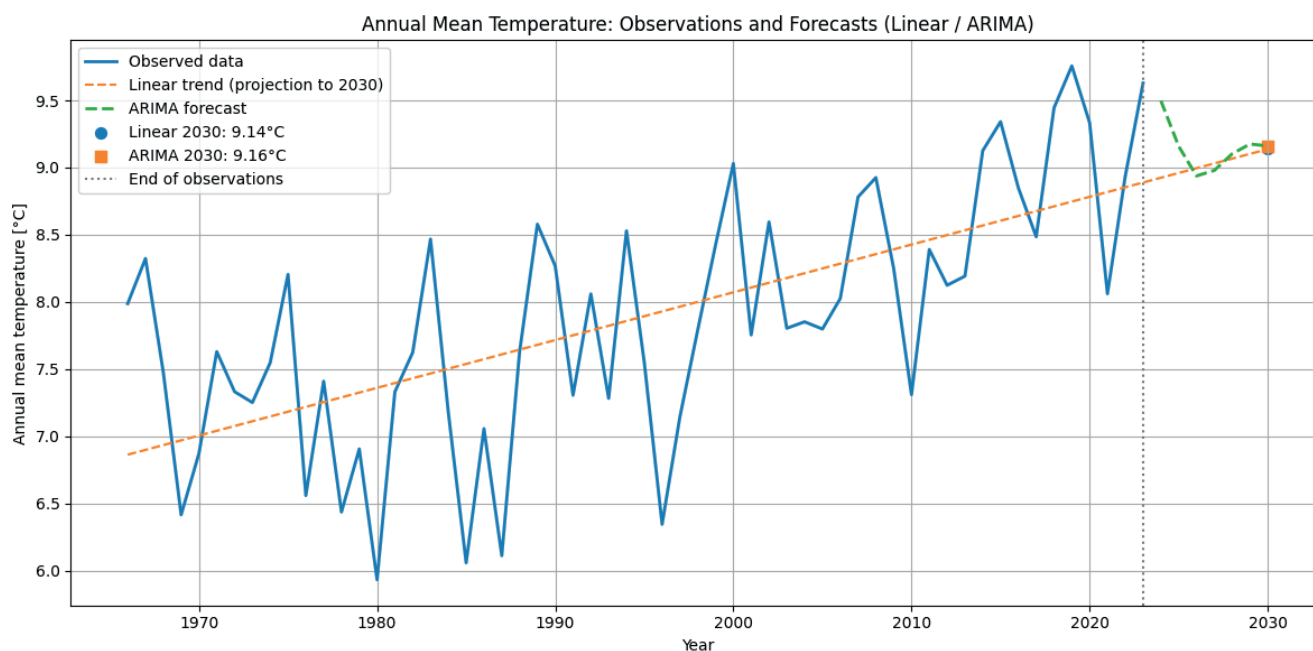


Fig. 10. Annual mean temperature trends with linear projection and ARIMA forecast to 2030 based on historical observations

totals have remained relatively stable over the study period. This discrepancy may reflect the coarse spatial resolution of ERA5, which can smooth local variations, particularly for precipitation, whereas station measurements capture site-specific conditions more accurately.

Overall, the comparison demonstrates that ERA5 reanalysis provides a good representation of temperature trends at the local scale, but local precipitation patterns are less reliably reproduced. These findings highlight the value of combining long-term station observations with reanalysis data to assess regional climate changes, especially when considering impacts on agriculture and water resources.

DISCUSSION

The increasing trend of moisture deficit in Central and Southern Europe, driven by rising air temperatures and enhanced evapotranspiration, has been confirmed by Urban et al. (2022). One of the consequences of climate change is the disruption of the hydrological regime. Climate warming after 1988 has affected the depth of genetically diverse low flows in Polish rivers in different ways. Summer low flows — shaped by low or absent precipitation, high air temperatures, and elevated evaporation — generally deepened, especially in rivers located in central Poland. In contrast, warmer winters and more frequent mid-

winter thaws increased runoff in many rivers, leading to the shallowing or even disappearance of winter low flows (Wrzeńska and Wrzeński 2023).

In recent decades in Poland, particularly in the Świętokrzyskie region, a clear increase has been observed in the frequency and intensity of heatwaves and drought periods, which heightens the risk of compound extreme events with complex environmental and socio-economic impacts. These phenomena pose serious threats to water resources, ecosystems, and public health (Ciupa and Suligowski 2020; Szwed et al. 2023). As emphasized by Ciupa and Suligowski (2009), a key component of climate change adaptation is the development of small retention systems and improved water resource management, aimed at enhancing hydrological and ecological stability in both rural and urban areas. In Kielce, the water supply system is particularly sensitive to climate change, especially during droughts occurring in combination with high temperatures (UM Kielce, 2018). This vulnerability is linked to the formation of a shallow yet extensive depression cone near the Białogon groundwater intake, caused by intensive exploitation and a high share of impervious surfaces within its recharge zone. This intake supplies approximately 64% of the city's population. Simultaneously, water demand increases during heatwaves and droughts. Water shortages also strongly affect agriculture in the Świętokrzyskie region; in recent years, spring drought has impacted most cereal

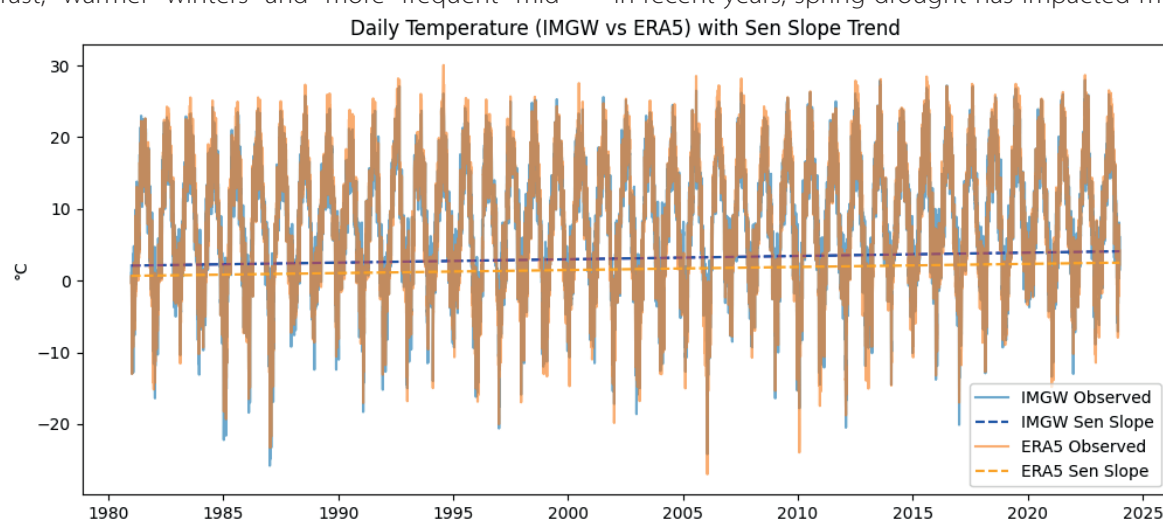


Fig. 11. Daily mean temperature in the Kielce region from IMGW station measurements (blue) and ERA5 reanalysis data (orange) for the overlapping period. Dashed lines represent the Sen Slope trends for each dataset, indicating a statistically significant warming trend in both datasets

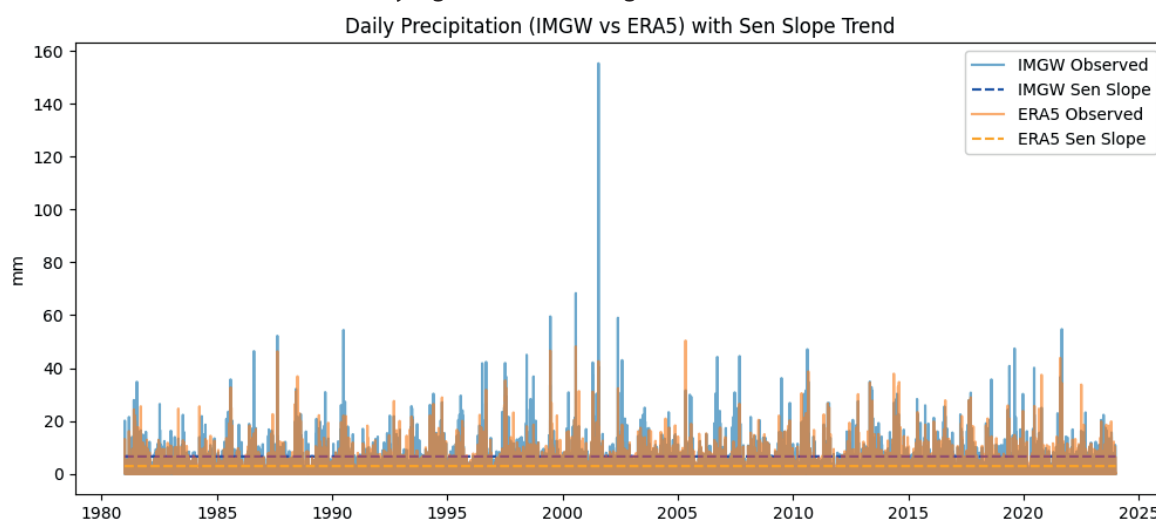


Fig. 12. Daily precipitation totals in the Kielce region from IMGW station measurements (blue) and ERA5 reanalysis data (orange). Dashed lines show the Sen Slope trends, indicating a weak decreasing trend in station data and no significant trend in ERA5 reanalysis

crops, shrubs, and fruit trees, causing yield losses of 30–50% (IUNG-PIB, 2024). In 2024, agricultural drought affected 68 out of 102 municipalities in the voivodeship.

Research by Ciupa and Suligowski (2020) highlights that urbanization, particularly in cities such as Kielce, significantly alters the hydrology of urban catchments. Differences in land use within the Silnica and Sufraganiec catchments influence both the speed and volume of surface runoff, thereby intensifying local heatwaves and increasing the risk of droughts and flash floods (Ciupa and Suligowski 2014a; 2014b). These hydrological changes also affect pollutant transport, placing additional stress on aquatic ecosystems (Ciupa and Suligowski 2020).

At the national scale, IMWM data show a steady increase in the number of days with maximum temperatures above 30°C (IMWM 2020). Combined with decreasing precipitation sums and longer dry spells, these changes contribute to the intensification of meteorological and hydrological droughts (Kundzewicz et al. 2018). Rising air temperatures strengthen evaporative demand, reducing water availability for agricultural and municipal purposes, particularly in low-retention regions such as Świętokrzyskie (Ciupa and Suligowski 2018).

The results of phenological analyses, indicating an advancement of certain seasons and an extension of the growing period, are consistent with observations from other regions of Poland and correspond with global trends in air temperature rise (Cleland et al. 2007; Tomczyk and Szyga-Pluta 2016). Phenological studies conducted by the Institute of Meteorology and Water Management – National Research Institute (IMWM) for the period 2007–2018 show a clear advancement in the onset dates of early spring and spring, as well as a slight delay in the beginning of autumn. For early spring, spring, and full spring, the onset advanced by 9–11 days relative to the 1951–1990 reference period, while the onset of autumn was delayed by 3 days. Consequently, the length of the growing season increased by approximately 12 days (Chojnacka-Ożga and Lorenc, 2019).

From a public health perspective, heatwaves are associated with increased hospitalizations and mortality related to cardiovascular and respiratory diseases, especially among vulnerable groups such as the elderly and children (EEA 2023). In Poland, an increase in heatstroke and other heat-related illnesses has been observed during periods of extreme heat (Szwed 2018).

The results obtained for the Kielce-Suków station correspond to warming trends recorded in other regions of Poland. Temperature statistics based on data from synoptic stations, calculated in accordance with the WMO Guidelines on the Calculation of Climate Normals (WMO-1203) for the 1991–2020 normal period, confirm the direction and magnitude of change observed in Kielce. The course of this trend varies according to local topographic and geographic conditions. Particularly valuable in this context are studies conducted within the Integrated Environmental Monitoring Network, which collects meteorological data representative of Poland's landscape zones, delineated according to the geoecosystem concept (Kostrzewski and Stach 1992).

Analyses of heatwaves and droughts in the monitoring network indicate a clear increase in the frequency of heatwaves in recent decades, consistent with global warming trends. In the 2010s and 2020s, heatwaves occurred in 60–70% of years, demonstrating a marked intensification of extreme heat events. Droughts remain a persistent climatic issue, with the highest frequency noted in the 1980s, followed by a decline and a moderate resurgence in recent years. The growing concurrence of heatwaves and droughts highlights an increasing risk of compound extreme weather events that

pose significant threats to water resources, ecosystems, and public health. These findings underscore the need for effective adaptation strategies, enhanced water management, and improved preparedness measures to mitigate the impacts of these climatic hazards.

Long-term air temperature measurements at Integrated Environmental Monitoring base stations show an unfavorable trend of rising mean annual temperatures. A statistically significant upward trend ($p < 0.05$) was identified for 8 out of 11 stations with at least a 10-year measurement record: Wolin, Parsęta, Puszcza Borecka, Chełmno Lakeland, Kampinos, Łysogóry, Carpathian Foothills, and the Low Beskids. The average 10-year increase in mean air temperature is 0.71°C per decade. The highest trends, exceeding 0.7°C, were recorded at Wolin (1.28°C) and Kampinos (0.75°C), while the lowest values, below 0.5°C, were observed at the Chełmno Lakeland station (0.45°C).

A series of studies conducted in Poland indicate that warming is one of the most pronounced and statistically significant elements of climate change in the region, with particularly rapid temperature increases observed during the winter and summer months. Analyses covering dozens of meteorological stations have shown that the annual mean temperature in Poland is rising at a rate of approximately 0.2–0.3°C per decade, which is consistent with trends observed in many cities, including those in the central and southern parts of the country (Kejna and Pospieszńska 2023; Kundzewicz et al. 2019). The observed temperature changes in Kielce align well with these nationwide patterns.

An important aspect of contemporary climate change is also the increase in the frequency and intensity of heat extremes. Studies by Wibig et al. (2009) demonstrated a clear rise in the number of hot days and tropical nights in Poland, especially after 1990. This trend is also characteristic of Eastern Europe, where heatwaves are occurring more frequently and lasting longer (Russo et al. 2015). The results from Kielce, indicating rising maximum temperatures, are consistent with this broader European pattern.

In contrast, precipitation variability and trends in Poland are considerably more spatially and seasonally diverse. Numerous studies have highlighted that, despite some upward trends in summer precipitation in certain parts of the country and downward trends during winter, the climatological signal of precipitation is weak and statistically unstable (Łupikasza 2010; Szwed 2018). For this reason, the lack of a clear direction of precipitation changes in Kielce aligns with the literature – many stations in Poland show a similar picture of high interannual variability and difficulty in identifying persistent trends.

Similarly, the observed shortening of snow cover duration in Kielce is a well-documented trend nationwide. Analyses conducted since the mid-20th century indicate a systematic reduction in the length of snow cover periods and a decrease in maximum snow depths across most regions of Poland, particularly in lowland areas (Falarz 2007). The reduction in snow cover is also a characteristic feature of climate change in Eastern Europe, associated, among other factors, with the rapid pace of winter warming and more frequent occurrences of temperatures crossing 0°C (Bulygina et al. 2011).

CONCLUSIONS

The analysis of long-term meteorological data from Kielce clearly documents significant climate changes in the Świętokrzyskie region. Thermally normal months remain the most common, but in recent decades, the frequency of warm and very warm months has increased, consistent with regional and national warming trends. Concurrently,

the number of cooler months has declined, with the most pronounced decrease observed in the “slightly cold” class.

Long-term snow cover analysis (1966–2024) indicates a gradual reduction in both duration and thickness, with persistent snow cover (≥ 30 days) becoming increasingly rare after the 1990s. Winters are now shorter and less snowy, with more frequent thaw events, reflecting broader regional warming trends.

The results highlight an increasing co-occurrence of heatwaves and droughts, particularly since the 2010s, when heatwaves affected 60–70% of years. Droughts, while peaking in the 1980s, have reappeared recently. These trends indicate the region’s growing exposure to compound climate extremes.

Importantly, these observed climatic changes have direct implications for regional vulnerability:

1. Water resources: Reduced snow cover and prolonged warm periods increase the risk of low river

flows and groundwater depletion, stressing municipal and agricultural water supplies.

2. Agriculture: Rising temperatures and extended dry spells heighten the risk of crop losses, particularly for cereals, fruit trees, and shrubs.

3. Urban planning and infrastructure: Higher frequency of heatwaves and combined drought conditions demand adaptive strategies for urban water supply, stormwater management, and public health preparedness.

In summary, while the study confirms ongoing warming and declining snow cover in central Poland, the applied relevance is clear: proactive adaptation in water management, agriculture, and urban planning is essential to mitigate the impacts of these climate changes. Integrating these findings into regional policy and management strategies can help enhance resilience against increasing thermal and hydrological extremes. ■

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SIMULATION OF THE WATER REGIME OF TWO LARGE EUROPEAN RUSSIA RIVERS UNDER THE CONDITIONS OF MODERN CLIMATE IN THE TERM LAND SURFACE MODEL

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ABSTRACT. The paper is devoted to the application of the TerM land surface model to reproduce the water regime of typical watersheds of the European part of Russia (Vychevda River, Oka River) under the conditions of modern climate. The work evaluates the quality of the TerM model with respect to the main components of the water regime in regional climatic conditions: long-time runoff mean, mean snow water equivalent at the beginning of melting, volume and dates of spring floods in the studied catchments. The quality of the model is assessed by comparing the results of numerical experiments with observational data. To obtain optimal results, a number of model improvements are proposed, in particular: accounting for artificial irrigation of cultivated plants in the process of transpiration, calibration of the infiltration capacity parameter of watershed soils, roughness Manning coefficient for river bed and coefficient of river network tortuosity. The TerM model with the proposed modifications successfully reproduces main characteristics of the water regime in the studied catchments.

KEYWORDS: land surface models, river water regime under modern climate conditions, model calibration.

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INTRODUCTION

The TerM land surface model [34] is a numerical process-based model of the dynamics of thermodynamic, hydrological and biogeochemical processes in the active layer of the Earth's land. The model equations describe the dynamics of soil heat content, moisture, water vapour and ice, carbon dioxide and methane, carbon stocks and fluxes. The TerM model originates from the land surface block of the INMCM Earth System Model [38], implemented as an independent software code for simulations with prescribed atmospheric forcing. Within the TerM model, the initial code of the INMCM model was supplemented with a number of modifications, mainly related to the clarification of hydrological and carbon cycle processes, particularly for geographical conditions of Russia. The TerM model is used to develop and test promising physical parameterizations for the INMCM model and has been used for research of current state and anticipated response of ecosystems to future climate change in Russia.

In the original INMCM model, as in Earth System models in general, the hydrological simulations focus on

reproducing the long-time runoff mean from the largest river catchments, which is necessary to describe the influence of hydrology on the thermohaline circulation in the ocean. At the same time, detailed representation of the intra-annual distribution of runoff and hydrographs on individual rivers is not usually considered a priority. However, the necessity for detailed reproduction of river runoff in Earth System models is gradually increasing with the increasing complexity of ocean models [15], the sophistication of carbon cycle parameterizations [21, 27], and improvements in atmospheric models to reproduce anomalous synoptic situations [19]. Also, the detailed representation of river runoff in Earth System models would facilitate hydrological predictions under different scenarios of anthropogenic impact or climate change for both well-studied and unexplored catchments, while the performance of statistical hydrological models in the same tasks is prone to overfitting the observational data [4]. At the side of hydrological modelling, a trend in the same direction, expressed in increasing of model robustness due to using of land-surface modelling approaches, can be noted (e.g., physically-based ECOMAG model [11]).

As part of the development of the hydrological compartment of the TerM model, a number of advancements were performed to the original INMCM model. A one-dimensional model of the river flow was incorporated in the TerM model to represent the water mass transport through the river network and river thermodynamics [35]. The model input data on the geographical distribution of land surface properties were updated [28, 29], in particular, those used for simulations of Russian territory. Substantial efforts were devoted to improving the TerM model's capability to reproduce the features of the water regime of rivers in the northern part of the East European Plain (Northern Dvina and Pechora river basins): the model's ability to simulate the key elements of the land hydrological cycle was studied and improved in terms of evaporation and transpiration [22], snow water equivalent [23], infiltration processes in frozen soil, and spring flood runoff formation [24].

In this paper we apply the TerM model to reproduce the water regime of rivers located at the northern and central parts of the European territory of Russia. The Vychegda and Oka rivers were selected as the study catchments. These catchments represent typical conditions of the water regime for the northern and central parts of the East European Plain, and successful reproduction of their runoff in the TerM model will indicate the acceptable quality of the model for a large part of the Russian territory. The novelty of this study lies in its application of TerM for regions with drier climate and under intense anthropogenic impact compared to those previously studied. In addition, so far the TerM model output has not been analyzed in terms of runoff hydrographs of rivers of comparable catchment area (the model was used only for the largest river basins or small elementary catchments [22, 24]). In the future, the TerM model can be applied to carry out simulations with these catchments under past and future climatic conditions and to assess the impact of climate change on river flow.

The purpose of this work is to analyze and improve the reproduction of the mean annual runoff hydrograph in the TerM model for the Vychegda and Oka rivers. For this purpose, we consider the quality of simulation of the main characteristics of the catchment water balance: multiyear-average runoff mean, snow water equivalent (SWE) at the beginning of melting, volume and dates of spring flood runoff. The quality of modelling is assessed on the basis of the results of numerical experiments with the model with prescribed atmospheric forcing. Based on the results of comparison of simulation results with observational data, a quantitative quality assessment is performed for the model, improvements in parameterizations of physical processes, and changes of calibration parameters are proposed.

MATERIALS AND METHODS

The main structural component of the TerM model is a solver for a system of one-dimensional equations of heat and moisture transport in a vertical soil column, which is applied in the cell centers of a regular latitude-longitude grid, with standard resolution $0.5^\circ \times 0.5^\circ$. The depth of the soil column is assumed to be 10 m, and the equations are discretized at 24 vertical levels. At the upper boundary of the column (ground surface), the heat and water balance is evaluated taking into account the mosaic coverage of the cell by different types of surface (11 types of natural vegetation from SiB classification [7], 2 types of agricultural land, altogether grouped as a single vegetation tile, open soil tile, snow cover tile, intercepted moisture tile and

open water tile represented by LAKE model [33]); zero-flux condition for diffusive transport of heat and liquid water are used as lower boundary conditions. The snow cover and a layer of intercepted moisture can be formed on the surface of the cell. Also in the cell, in case of water bodies, there can be an additional column representing the water body, in which the equations of heat, momentum and mass transfer in the aquatic environment are solved. Between the land cells, the water mass transport through the river network is performed using a diffusion wave type river network model [35]. The input data of the model include external parameter datasets (see below) provided by TerMPS package [29], which are used to specify the differential equations' coefficients, as well as atmospheric surface layer variables including temperature, specific humidity, surface air pressure, wind speed, precipitation rate, incoming shortwave and longwave radiation fluxes involved to specify the top boundary conditions.

In the heat balance of the land surface, the TerM model takes into account the shortwave (radiation balance of soil and snow under the vegetation canopy are set according to the vegetation radiation transfer model [6, 32]) and longwave radiation fluxes, the turbulent fluxes of heat and moisture (to evaluate the turbulent exchange coefficients, dimensionless Monin-Obukhov similarity theory (MOST) stability functions are used, while the dynamic and thermal roughness parameterizations specific to different types of surface are taken into account [36]; the model of stomatal conductivity [31] is used to represent transpiration – see below), heat effects of snow melting and freezing, and heat flux into the underlying soil. The water balance at the surface takes into account the snow melting rate and intercepted moisture throughfall, as well as infiltration into the soil and the formation of slope runoff when the maximum infiltration rate is exceeded and when water enters moisture-saturated soil areas [8]. In the snow cover, a system of equations for vertical heat and melt water transport and snow density dynamics is solved; these equations are discretized at 4 vertical levels [23]. In the soil column, heat and moisture transport under the action of diffusion and capillary forces is described; phase transitions of water, water withdrawal during transpiration, and formation of subsurface runoff are taken into account [8]. An additional component of subsurface runoff to rivers is also the percolation flux through the lower boundary of the soil column. A number of the model parameters can be calibrated to achieve a better fit to the observed data.

In the context of this article, it is necessary to focus in more detail on transpiration and runoff parameterizations. Transpiration of vegetation cover, including cultivated vegetation, is calculated in the TerM model according to the concept of resistances as:

$$E = \rho \frac{\Delta q}{r_a + r_{s,total}} \quad (1)$$

where E - transpiration rate [$\text{kg}/(\text{m}^2 \times \text{s})$], Δq - difference of specific air humidity at the height of the atmospheric surface layer and inside the vegetation cover [g/g], ρ - air density [kg/m^3], r_a and $r_{s,total}$ - aerodynamic and stomatal resistances of water vapour transport in the surface layer of the atmosphere [s/m]. The value of aerodynamic resistance characterises the efficiency of water vapour transport by turbulent vortices, while the stomatal resistance is linked to the degree of openness of plant leaves stomata, which determines the efficiency of water vapour diffusion from plant tissues into the atmosphere. The stomatal resistance of the vegetation cover $r_{s,total}$ is evaluated by integrating the expression for the stomatal resistance of a single leaf r_s over the thickness of the vegetation cover,

taking into account the photosynthetically active radiation attenuation [31]. The expression for an individual leaf is written within the multiplicative model expressing the concept of limiting factors [18]:

$$\frac{1}{r_s} = \frac{1}{r_{s,min}} \times f_P(P) \times f_T(T) \times f_d(d) \times f_W(W) \quad (2)$$

where $r_{s,min}$ is the minimum stomatal resistance given by the constant, individual for each plant functional type [c/m]; $f_P(P)$, $f_T(T)$, $f_d(d)$, $f_W(W)$ are functions of photosynthetically active radiation P , temperature T , air moisture deficit d and soil moisture W , respectively. These functions take values from 0 to 1 and characterise the degree of opening of stomata on plant leaves depending on environmental factors. The function $f_W(W)$ for soil moisture has the following form:

$$f_W(W) = \frac{W - W_{wilt,end}}{W_{wilt,start} - W_{wilt,end}}, \quad (3)$$

$$0 \leq f_W(W) \leq 1$$

where W - integral moisture in the root-inhabited soil layer [m]; $W_{wilt,start}$, $W_{wilt,end}$ - integral moisture at the beginning of wilting process and intensive wilting respectively in the root-inhabited soil layer [m] (the integral weights the soil moisture with the density of the root system). When calculating the parameters $W_{wilt,start}$ and $W_{wilt,end}$ the values of the soil water potential of the beginning of wilting and intensive wilting are used, which are considered constants individual for plant functional types of vegetation; for 2 types of agricultural land (arable land and tree plantations) the moisture potential of the beginning of wilting is set to -10000 cm and -19000 cm, the moisture potential of intensive wilting is -20000 cm and -25000 cm, respectively. Under moisture deficit conditions, the function $f_W(W)$ is the main limiting factor for plant transpiration. At this paper, in order to describe the effect of artificial irrigation of cultivated land in the TerM model for the corresponding vegetation types, it was supposed

$$f_W(W) = 1 \quad (4)$$

One of the components of total river runoff (surface infiltration-excess runoff), considered in this paper, is calculated as [25]:

$$R_{s,inf} = B - B_{cap} \times (1 - \exp(-B/B_{cap})) \quad (5)$$

$$B_{cap} = \gamma_{max} I_{z=0} \times k$$

where $R_{s,inf}$ - surface slope runoff due to infiltration excess [m/s], B - water flux to the soil surface (consisting from liquid precipitation and melt snow water rate) [m/s], B_{cap} - maximum infiltration rate into the soil [m/s] which depends on the soil type, γ_{max} - maximum hydraulic conductivity in the soil column [m/s] in the depth range $z \in [0; h_{soil}]$, where $z=0$ - soil surface, $z=h_{soil}$ - lower boundary of the soil column; k - dimensionless calibration factor. The transfer of runoff through the river network is described by the diffusion wave model of riverflow dynamics [35]. In this model, the following equation is implemented to calculate the flow velocity in the cross section of the channel:

$$U = U_o \times \left(1 - \frac{1}{2s} \frac{\partial h}{\partial x}\right), \quad (6)$$

$$U_o = \frac{1}{n} R^{2/3} s^{1/2}$$

where U is the flow velocity in the channel [m/s], R is the hydraulic radius [m], h is the river depth [m], s is the tangent of the slope angle of the channel thalweg, n is the Manning roughness coefficient [$s m^{-1/3}$], x is the horizontal coordinate directed along the channel thalweg. The equation is solved using a finite-difference scheme along the x -axis; at the same time, the mesh spacing between nodes is corrected for the tortuosity of the channel network:

$$\Delta x = m \times \Delta x' \quad (7)$$

where Δx is the value of grid spacing along the channel thalweg [m], $\Delta x'$ is the value of grid spacing assuming straight channels connecting neighboring cells [m] [35], m is the tortuosity coefficient.

TerM uses external databases to specify maps of a number of model parameters: the map of terrestrial ecosystems of Russia by ICR RAS [39] for land cover types, GLCC database [20] for the same but outside Russia; GLDBv2 database [2] for depths and areas of water bodies; database [5] for hydrophysical properties of soils, digital model ETOPO1 [1] for surface elevation, DDM30 [30] for river flow directions, MODIS data [10] for leaf index of vegetation. The TerMPS package of unified algorithms [29] is used for aggregation of the data from original resolution of above listed databases onto the model grid.

It is known that the main factors affecting the perennial runoff rate are precipitation and evapotranspiration from the catchment surface. The magnitude of spring flood runoff, which is the most characteristic feature of the water regime of the studied rivers, is formed due to the magnitude of SWE at the beginning of melting, the amount of precipitation during the flood period and the magnitude of infiltration losses at the catchment [37]. Errors in precipitation, which is an input parameter for the TerM model, can be considered negligible if a representative source of precipitation data is selected. Thus, in order to verify the main factors of river runoff formation at the catchment, it is necessary to analyze the mean annual runoff (to assess the quality of modeled evapotranspiration), the SWE at the beginning of melting (as the main factor of spring flood runoff formation) and the analysis of annual runoff hydrographs (to assess the quality of flood runoff simulation). This analysis was carried out by comparing river runoff and SWE provided by the TerM model with observational data.

The Vychegda River catchment is located in the middle taiga zone, the precipitation-evaporation ratio is about 1.5, the landscapes are represented mainly by dark coniferous, light coniferous, small-leaved and mixed forests; anthropogenic impact on the catchment area is minimal. The Oka River catchment is located in the zone of broadleaved forests, the precipitation-evaporation ratio is about 1.0, natural landscapes are represented by mixed and broadleaved forests; in contrast to Vychegda, a significant share of the area is occupied by agriculture lands and meadow vegetation. The natural landscapes of the Oka River catchment have been significantly altered by anthropogenic factors. Both catchments are characterised by predominantly snow feeding of runoff with pronounced spring flooding and stable winter low-water periods; the Oka River is characterised by a greater contribution from ground feeding and sometimes interruption of low-water periods by flooding due to thaws. The runoff of both rivers is insignificantly regulated [9, 39]. For the water discharge, we selected observations at the closing river gauges of the studied basins: Koryazhma station (32 km from the mouth of Vychegda, upstream runoff area 119 thousand km²) and Gorbato station (78 km from the mouth of Oka, upstream

area 244 thousand km²). The period 2008-2020 was chosen for model-observations comparison; TerM model runs were performed for the period 2000-2020 (with spinup period of 8 years, primarily to bring the soil moisture to equilibrium with long-term atmospheric conditions) with a time step of 1 hour and a spatial resolution of 0.5°×0.5° (82 cells for Vychegda basin and 134 cells for Oka basin). The ERA5 reanalysis data [14] (spatial resolution 0.5°×0.5°, time resolution 1 hour) were used as atmospheric forcing except precipitation, and the GPCP 3.2 data [16] (spatial resolution 0.5°×0.5°, time resolution 1 day) were used as input data on atmospheric precipitation; daily mean intensity was used at each time step of the model within a day. The error in atmospheric forcing data in the study area was considered negligible [12, 26].

To assess the quality of SWE simulation, the TerM model output was compared with data from route snow measurement surveys conducted at meteorological stations within and in the immediate vicinity of the study catchments (4 stations for the Vychegda River and 9 stations for the Oka River). Observational data represent measurements of SWE each 5-10 days; data from routes in non-forested landscapes were selected for analysis. Observational data were linearly interpolated over time to obtain averaged seasonal dynamics. The period 2000-2020 was chosen for model validation; TerM model simulations were performed in a single-column mode for the same period with a time step of 3 hours at weather station points. In these numerical experiments, instantaneous 3-hourly observational data at meteorological stations were used as input data; the ERA5 reanalysis [14] was used for the magnitudes of incoming shortwave and longwave radiation fluxes, as well as to fill the gaps in station data for other variables.

RESULTS AND DISCUSSION

Table 1 compares the results of the TerM model simulation of the long-term runoff mean in the Vychegda and Oka basins with the observed data. The observed model deviation in the mean value is acceptable compared to the annual precipitation (overestimation by 7-8% in both catchments). However, compared to the value of the runoff rate, the error is more significant (overestimation by 17.8% for the Vychegda River and 34.8% for the Oka River). The overestimation of the runoff norm in the model indicates an underestimation of the summer evapotranspiration norm from the catchment (precipitation from GPCP are close to observational data [16], winter evapotranspiration reproduced with high accuracy as shown below for SWE). At the same time, the

relative error for the Oka River is almost twice as large as for the Vychegda River. We hypothesised that the larger error for the Oka River was due to an overestimation of the effect of wilting vegetation during drought periods in cultivated agricultural areas, which are widespread in the catchment of the river. In most agricultural areas, artificial irrigation of crops and maintenance of their optimal moisture regime are carried out on a permanent or one-time basis during periods of drought. This anthropogenic factor is not taken into account in the TerM model, which may result in an overestimation of evapotranspiration. A modification of wilting multiplier (3) for parameterization of transpiration was proposed for the TerM model in the form of parametrization (4). Although this parameterization is very simplified (possibly overestimating the effect of irrigation), it can nevertheless be considered that it reflects the physical consequences of irrigation and can be used as one of the options for parameterizing anthropogenic effects in the TerM.

The results of TerM model for Oka river with this modification are presented in Table 1 - the proposed parameterization reduced the relative error to a level comparable to the Vychegda River. The obtained overestimation of the mean annual runoff by 13.3% for the Oka River and by 17.8% for the Vychegda River can be considered acceptable. The observed error may be related to the magnitude of stomatal resistance parameters for different vegetation types, LAI data, etc.

Table 2 presents the metrics of the TerM model error in the magnitude of maximum SWE (SWE by the beginning of melting) according to route measurements within the studied catchments. The values obtained indicate a significant scatter in the observed error both between different stations (relative error of mean ranging from -29.4% to +38.4%) and for each individual station between different years (correlation coefficient values for the time series from 0.35 to 0.87). However, the error metrics for the values averaged over a set of meteorological stations show acceptable values (overestimation by 4.4% for the Vychegda River, by 7.3% for the Oka River). A significant part of the model error and low values of error metrics at individual stations may be related to local factors (wind redistribution, blizzards, etc) in the snow measurement data that influenced the dynamics of snow accumulation in a particular year for a particular location [23]. This variability can be eliminated by averaging. We assume that the error over the catchment surface as a whole will be close to the error obtained over the set of stations.

Figure 1 compares the SWE averaged over all meteorological stations within the study catchments and all winters in the period 2000-2020 provided by the TerM

Table 1. Average runoff depth for 2008-2020 for the Vychegda and Oka rivers. Vychegda and Oka rivers according to observations and the TerM model output

	Vychegda	Oka	
		model, basic version	model, modified version
Precipitation, mm	764.0	702.7	
Runoff depth (observations), mm	345.1	151.3	
Runoff depth (model), mm	406.4	203.8	171.5
Absolute error, mm (±interannual standard deviation of error, mm)	+61.26 (±3.88)	+52.59 (±1.54)	+20.24 (±1.15)
Error relative to precipitation amount	+8.0%	+7.5%	+2.8%
Error relative to runoff depth	+17.8%	+34.8%	+13.3%

model and observations. In the averaging procedure, instead of the mean the median was calculated, due to the significant heterogeneity of samples during the periods of snow accumulation and snowmelt. The model correctly reproduces basic features of snow accumulation dynamics, such as the timing of snow cover emergence, the timing of the beginning of melting, the intensity of melting and the timing of snow cover melting. It should be noted that this was estimated only for snow cover at field landscapes, while part of the error of the model in spring flood runoff may be associated with errors of the snow dynamics at the forest, associated with the errors in taking into account the processes of radiation and turbulent transfer at the canopy.

Table 3 presents a comparison of the average spring flood depth (the spring flood depth is computed from the average hydrograph as an integral for part of curve

which exceeding of the baseflow line) for the Vychegda River and the Oka River according to the TerM model and observations. Fig. 2 shows the corresponding mean runoff hydrographs. The results indicate an underestimation of the flood runoff volume and earlier timing of spring flood in the non-calibrated version of the TerM model. The observed error can be controlled by the values of the calibrated model parameters: the infiltration capacity parameter of the upper soil layer in the catchment, the roughness parameter in the river channels, and the tortuosity coefficient of the river network.

The calibration factor k for the infiltration capacity parameter of the topsoil is included in the equation for calculating the surface component of catchment runoff (5) [25], which is formed when the rate of water flux to the soil surface exceeds the maximum rate of infiltration through

Table 2. Average maximum snow water equivalent (SWE) at meteorological stations within the catchments of the Vychegda and Oka rivers for 2000-2020 based on observations and TerM model

Station	Average maximum SWE (observations), mm	Average maximum SWE (model), mm	Absolute error, mm ($\pm$ interannual standard deviation of error, mm)	Relative error, %	Correlation coefficient for the time series
Vychegda River					
Veliky Ustyug	180.0	177.7	+6.79	+4.0%	0.35
Oparino	190.2	196.2	+5.99	+3.1%	0.57
Sura	135.1	159.0	+23.88	+17.7%	0.83
Ust-Tsilma	188.2	182.2	-5.96	-3.2%	0.64
for the set of stations	171.1	178.8	+7.7 ($\pm$ 37.0)	+4.4%	0.62
Oka River					
Bryansk	92.7	117.9	+25.18	+27.2%	0.80
Yelatma	101.6	135.1	+33.56	+33.0%	0.77
Kostroma	122.1	92.0	-30.10	-24.7%	0.69
Lukoyanov	103.2	112.3	+9.15	+8.9%	0.75
Mozhaisk	81.7	113.1	+31.38	+38.4%	0.81
Pavelets	105.7	74.7	-31.05	-29.4%	0.66
Penza	100.4	100.6	+0.13	+0.1%	0.87
Ponyri	92.2	92.5	+0.36	+0.4%	0.76
Sukhinichi	77.0	103.6	+26.6	+34.6%	0.87
for the set of stations	97.4	104.6	+7.1 ($\pm$ 37.7)	+7.3%	0.65

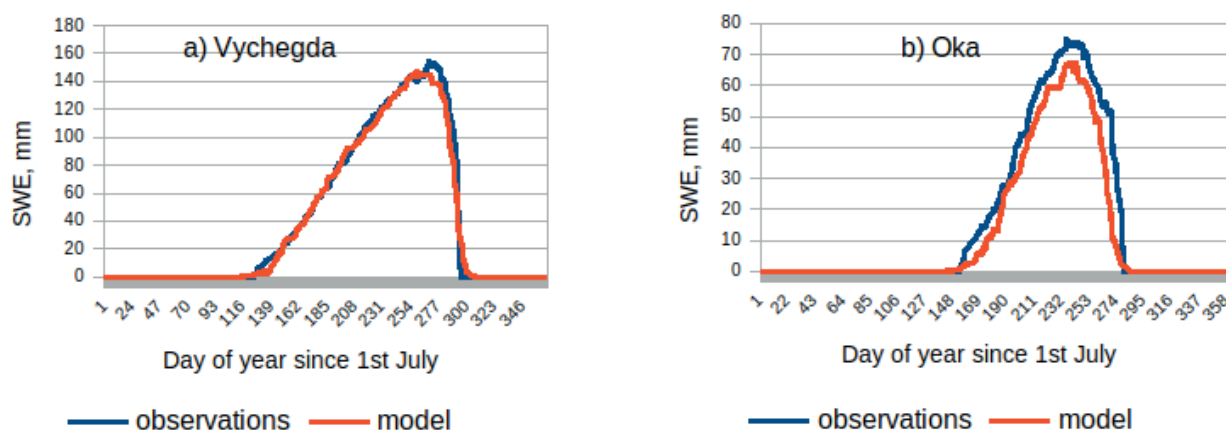
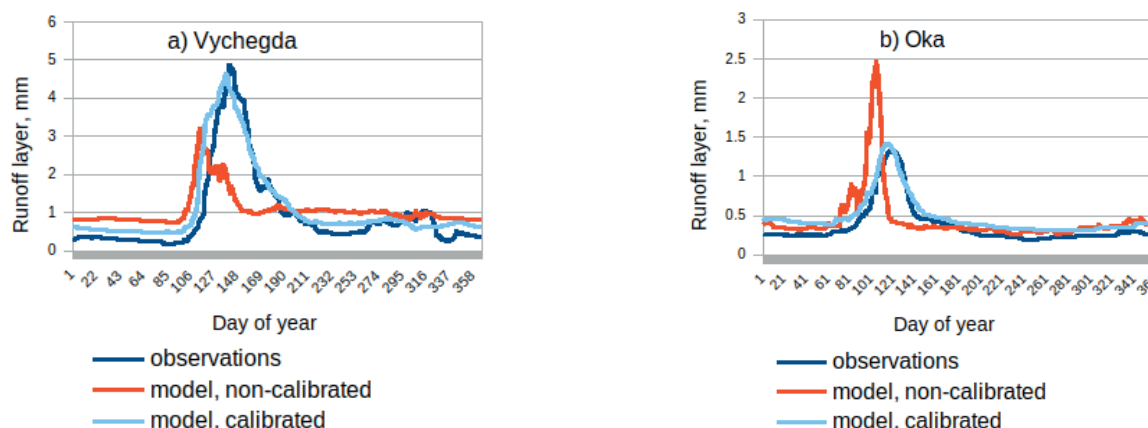


Fig. 1. Average seasonal course of snow accumulation at meteorological stations within the catchments of a) Vychegda River and b) Oka River for 2000-2020, based on observations and TerM model

Table 3. Spring flood runoff depth extracted from the mean hydrograph for the Vychegda and Oka rivers, 2008-2020, based on observations and TerM results

	Vychegda River		Oka River	
	model non-calibrated	model, calibrated	model, non-calibrated	model, calibrated
Spring flood runoff depth (observations), mm	229.2		74.2	
Spring flood runoff depth (model), mm	107.79	259.5	57.5	85.0
Absolute error, mm ($\pm$ interannual standard deviation of error, mm)	-121.41 ($\pm$ 34.71)	+30.30 ($\pm$ 16.90)	-16.69 ($\pm$ 24.23)	+10.82 ($\pm$ 20.03)
Error relative to long-term runoff mean, %	-35.2%	+8.8%	-12.4%	+8.0%

**Fig. 2. Average annual hydrograph of the Vychegda and Oka rivers runoff depth for 2008-2020 according to observations and TerM model**

the topsoil (soil infiltration capacity) and is the main mechanism of spring flood runoff formation when soils on watershed are frozen. This equation is written under the assumption of a subgrid distribution of infiltration capacity within a latitude-longitude model grid cell according to an exponential distribution law with mathematical expectation B_{cap} . From a physical point of view, the value of B_{cap} should be related to the value of γ_{max} , representing the maximum hydraulic conductivity of the topsoil averaged over the cell. In the TerM model, the value of γ_{max} is obtained by averaging the original fine-scale input data on soil properties [5]. However, the γ_{max} values thus obtained often cannot provide the actual observed flood runoff volume according to equation (5), which is due to the large spatial variability of soil hydraulic conductivity in the catchment within several orders of magnitude, which is reflected in the input data with high uncertainty. A common approach in hydrological modelling practice is to calibrate the parameter B_{cap} for each individual catchment under study [25]. A similar approach has been implemented in the TerM model; in this case, the calibration factor k in formula (5) is set to a single value for all cells located within the study catchment. By default, k is assumed 1. Once the calibration factor decreases, an increase in flood discharge can be expected and *vice versa*; the range of possible values of k spans from 0.01 to 100 [28].

The channel roughness parameter (Manning's coefficient) and tortuosity coefficient of the river network are used in the diffusion wave model of riverflow dynamics (6-7) [35]. By default in the TerM model, the values of river model parameters are set the same constants for all rivers: the Manning coefficient n is $0.035 \text{ s} \cdot \text{m}^{-1/3}$ and the tortuosity coefficient m is 1.4. In reality, the values of these parameters vary considerably. The value of the Manning coefficient depends on the state of the watercourse bottom surface and varies from about 0.025 (for smooth channels with free flow) to 0.2 (for overgrown forested floodplains) [3].

During flooding and overflow periods, the flow enters the vegetated floodplain, which results in an increase of the roughness coefficient; accounting for this process in the model can lead to slowing down the flow and shifting the timing of floods to later dates. The possible range of tortuosity coefficient values can be from 1 to 3 or more; for the Oka River, the maximum values are of the order of 2.6 (in some sections) [17]. Greater tortuosity and, accordingly, greater channel length entails in a later onset of flooding, under other conditions fixed. Thus, the refinement of the Manning coefficient and tortuosity coefficient parameters for the studied catchments can improve the TerM model performance in the timing of floods so that their values are considered as calibration settings and determined to achieve an optimal fit of the model to the observed river discharge. Nevertheless, it should be taken into account that assessing these parameters on a global scale may be difficult.

To assess the magnitude of the calibration parameter values in the TerM model for the Vychegda and Oka catchments, a series of sensitivity numerical experiments were carried out with values of the k , m and n of different orders. The calibration was done using the enumeration method and the objective function was the Nash-Sutcliffe coefficient for the daily runoff series. As a first approximation, the value of the roughness coefficient was set constant throughout the year; one can expect less influence of this coefficient change on runoff during low water periods compared to spring floods. The parameter values that allowed to demonstrate the lowest level of errors in the volume and timing of spring floods were as follows: $k = 0.1$ for the Vychegda River, for Oka $k = 2.0$, for both rivers $n = 0.050 \text{ s} \cdot \text{m}^{-1/3}$, for both rivers $m = 2.5$. Comparison of the results of the calibrated TerM model with the observed data is presented in Table 3 and Fig. 2. The calibrated model shows much lower errors in spring flood volume and timing. Fig. 3 shows the series of daily

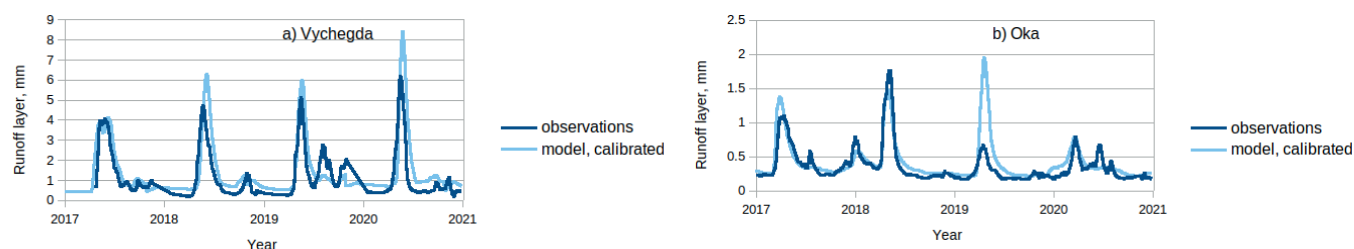


Fig. 3. Dynamics of daily runoff depth of the Vychegda River and Oka River for 2017-2020 according to observations and results of TerM model

values of the runoff depth for the studied catchments for a part of the analyzed time period. The model demonstrates realistic hydrograph pattern; the value of the Nash-Sutcliffe coefficient for Vychegda river is 0.67, while for the Oka river 0.62. The model overestimates the low-water discharge compared to the observed data which may be a consequence of errors in the reproduction of evaporation and errors in the calibration of spring flood runoff, and also does not well reproduce some flood events which may be related to the parametrization of groundwater and rain floods.

The values obtained are within physically reasonable ranges reported in literature. The value of the calibration coefficient for the infiltration capacity parameter obtained for the Vychegda River coincided with the optimal values of the order of magnitude obtained for the Northern Dvina River [24], for which the Vychegda River is a sub-basin. The Manning coefficient values obtained correspond to flow on a floodplain covered with cultivated crops or predominantly shrub vegetation [3]. The obtained coefficient of tortuosity values are close to the maximum values observed in these river sections along their entire length [17]. It is likely that the coefficient of tortuosity value obtained during the calibration process is slightly higher than the actual one, and the shift of optimal m from realistic value served to eliminate the errors of other model parameters as well as misrepresentation of physical processes.

CONCLUSIONS

As a result of a series of computational experiments, the TerM land surface model was shown to be of acceptable quality in reproducing the water regime of the Vychegda and Oka rivers under conditions of modern

climate (2008-2020), in particular, such characteristics as the long-term runoff mean (error with respect to the long-term precipitation mean +8.0% and +2.8%, respectively, and with respect to long-term runoff mean provided by river gauges +17.8% and +13.3%, respectively), snow water equivalent at the beginning of melting (error +7.7% and +7.1%, respectively), spring flood runoff volume (error +8.8% and +8.0%, respectively), dates of spring flood and annual hydrograph behavior in general (Nash-Sutcliffe coefficient 0.67 and 0.62, respectively). The obtained quality metrics may be insufficient in comparison with specialized hydrological models, but are quite high in comparison with other land surface models [13]. In the process of model calibration, values of calibrated model parameters, in particular, the coefficient for soil infiltration capacity parameter, Manning's roughness coefficient and river network tortuosity coefficient were obtained for the studied catchments; the obtained parameter values fell within the physically reasonable ranges reported in literature. Also, a modification of vegetation wilting parameterization was proposed for the model, which allows taking into account the effect of artificial irrigation of cultivated lands and allowed improving the results of annual discharge reproduction for the Oka River. Based on the results obtained, it can be concluded that the TerM model can be successfully applied to perform hydrological simulations in geographical conditions typical for a large part of Russia.

Further work will be continued in the direction of carrying out numerical studies with the TerM model for the Vychegda and Oka rivers under climatic conditions of the past and future and to assess the impact of climate change on the water regime of the European part of Russia. ■

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MODELING THE POTENTIAL DISTRIBUTION OF THE *IXODES PAVLOVSKYI* TICK AND ITS CHANGES UNDER CURRENT CLIMATIC CONDITIONS

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ABSTRACT. The tick *Ixodes pavlovskyi* Pomerantsev, 1946 is a vector of tick-borne encephalitis virus, *Borrelia*, and a number of other diseases. It is widespread in Siberia and the Far East, and its range has expanded in recent decades. The purpose of this study was to create a model of its potential distribution over three periods: 1961–1980, 1981–2000 and 2001–2020, during which strong climate change was observed. Modeling was performed using the MaxEnt algorithm. A total of 81 detection points were identified from literature and databases. Bioclimatic parameters were used as the only predictors because climate is apparently the principal factor limiting the distribution of *I. pavlovskyi*. Five bioclimatic parameters with the lowest pairwise correlations and their transformation functions were selected to provide the best model. Akaike Information Criterion corrected (AICc), Boyce Index, and Area Under Curve (AUC) were used as model quality metrics. In addition to known distribution areas, new potential territories of distribution with high suitability were identified, including those in Russia, Japan, Central Asia, the Caucasus, China, Canada, and the northern United States. According to the results of modeling, the greatest changes in the potential climatic range of *I. pavlovskyi* during the study periods occurred in the Siberian part of its range, where the area of high suitability expanded substantially during 2001–2020 as a result of climate change. In other regions, little shift in the potential range of *I. pavlovskyi* was observed. Also, it was identified that BIO1 (annual mean temperature) and BIO15 (precipitation seasonality) are the most important parameters for model construction.

KEYWORDS: climate change, ixodid ticks, *Ixodes pavlovskyi*, species distribution modeling, distribution shifts, MaxEnt

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INTRODUCTION

The tick *Ixodes pavlovskyi* Pomerantsev, 1946 (Acari: Ixodidae) is a bloodsucking ectoparasite of vertebrate animals (Filippova 1977). This species was first described in 1936 by the Soviet scientist B.I. Pomerantsev based on the female imago from a hazel grouse (*Tetrastes bonasia*) obtained in Primorsky Krai (Pomerantsev 1948; Pomerantsev 1950). The species was named in honor of the famous Russian and Soviet zoologist and parasitologist, academician E.N. Pavlovsky (1884–1965) (Dubinina and Nikitin 2020).

Larvae and nymphs of *I. pavlovskyi* feed on a wide range of small mammals and birds. The main hosts of adults are birds and, less often, mammals, including humans (Filippova 1977). *I. pavlovskyi* is a vector of pathogens of various dangerous vector-borne diseases, such as tick-borne encephalitis and Lyme disease (Chigirik et al. 1974; Korenberg et al. 2010). Its ability to transmit *Rickettsia* (Yakovchits et al. 2017), Kemerovo virus (Tkachev et al. 2017) and novel Haseki tick virus (Kartashov et al. 2023) has also been shown.

In recent years, there have been reports of an increasing number of bites by this tick on humans and domestic animals, as well as the discovery of this species in new regions. Several hypotheses have been put forward about the causes of these processes (Yakimenko et al. 2013). However, it can be stated with a high degree of certainty that the main reason for the expansion of the *I. pavlovskyi* range is the various climate changes observed in recent decades, associated with an increase in surface air temperature and changes in precipitation patterns (IPCC 2023a; Third assessment report ... 2022). In particular, the significance of the impact of climate change on the spread of vector-borne diseases, which make up the majority of infectious diseases worldwide, and their vectors is indicated in the Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, which included this climate-related hazard among the main socially significant risks from climate change (IPCC 2023b).

The *I. pavlovskyi* range consists of two distinct parts: eastern and western (Filippova and Panova 1998). The

main area of the range is located in the Russian Federation (Fedorov and Hornok 2024).

The eastern part of the range includes the southern part of Khabarovsk Krai and almost all of Primorsky Krai of Russia, including the adjacent islands of the Sea of Japan (Filippova and Beliaev 1970; Kolonin 1986; Nikitin et al. 2015). This part of the range also includes the northern regions of Japan, where in the early 1990s *I. pavlovskyi* was found on Hokkaido Island (Nakao et al. 1992), and in 2018 on Rishiri Island (Zamoto-Niikura et al. 2020).

The western part of the range of *I. pavlovskyi* primarily includes the territories of a number of Siberian regions of the Russian Federation – Kemerovo Region, Altai Krai, and the Republics of Altai and Khakassia (Sapegina and Ravkin 1969; Chigirik et al. 1972; Kovalevsky et al. 1975; Filippova 1977; Yakimenko et al. 2013; Nikoshenko and Zubova 2021; Fedorov and Hornok 2024). In these areas, *I. pavlovskyi* was discovered back in the 1960s and 1970s. At the beginning of the 21st century, its populations were discovered in the Novosibirsk and Tomsk regions (Grigoryeva and Livanova 2012; Livanova et al. 2016; Mikryukova et al. 2014). *I. pavlovskyi* was also found in the mountainous and foothill regions of Eastern Kazakhstan and Kyrgyzstan (Western Altai, Tien Shan, Dzungarian Alatau) (Filippova and Ushakova 1967; Ushakova et al. 1976; Livanova et al. 2016; Fedorova 2017).

There are several findings of *I. pavlovskyi* in the northwestern and northeastern provinces of China (Takada et al. 1998; Guo et al. 2016). These loci can be attributed to the western and eastern parts of its range, respectively.

As can be seen from the above, *I. pavlovskyi* is one of the most widespread and important species of the genus *Ixodes* for humans in Eurasia and is comparable in importance to the species *I. ricinus* and *I. persulcatus*. At the same time, if *I. ricinus* and *I. persulcatus* have been very well studied in a variety of aspects, the species *I. pavlovskyi* is significantly inferior to them in the degree of study.

Species distribution modeling (SDM) is a rapidly growing field of science at the intersection of ecology, biogeography, and information technology (Peterson et al. 2011; Araújo et al. 2019; Srivastava et al. 2019; Sillero et al. 2021). Almost all models of terrestrial species distribution involve climatic predictors, primarily temperature and precipitation, as being of primary importance for the vital activity of organisms and determining their distribution (Popova and Popov 2013; Popova and Popov 2019).

Currently, SDM uses various modeling algorithms. One of the most effective and frequently used methods is the MaxEnt algorithm (Phillips et al. 2004, 2006, 2017; Elith et al. 2010b; Lisovsky and Dudov 2021).

Numerous studies have addressed the modeling of the geographic ranges of different species of ixodid ticks and their changes over time, including using MaxEnt (Ogden et al. 2006; Porretta et al. 2013; Popov and Yasyukevich 2014; Hahn et al. 2016; Popov et al. 2021; Uusitalo et al. 2022; Kuyucu and Hekimoglu 2024). However, at the moment, there are no studies on modeling the possible distribution of *I. pavlovskyi* and its changes under observed changes in climatic conditions.

As noted earlier, *I. pavlovskyi* ticks are capable of feeding on a very wide range of hosts at all stages of their ontogenesis. There is also no evidence of predators or pathogens that limit their distribution. Therefore, climatic factors are likely to be the main limiting factors for the distribution of this species when the distribution is analyzed at a large spatial scale.

The aim of this study was to create a model of the potential worldwide distribution of the *I. pavlovskyi* tick in the climatic conditions of the second half of the 20th century and early 21st century. The potential distribution territory of this species was understood to be its climatic range, i.e., a geographic area where climatic conditions allow for the stable existence of a species (Popova and Popov 2013; Popova and Popov 2019). To assess shifts in the tick's climatic range under the influence of observed climate changes and to identify areas of its possible distribution, modeling was carried out for three periods: 1961–1980, 1981–2000 and 2001–2020. MaxEnt was used as a modeling method.

MATERIALS AND METHODS

Distribution data

The distribution data for *I. pavlovskyi*, which serve as the main material for constructing the SDM, were taken from two sources:

1. Global Biodiversity Information Facility (GBIF). The request yielded 92 records¹. Of these, records containing information about the year of the find and its exact coordinates were selected. After discarding duplicates and records with obviously erroneous information, 8 records remained.

2. Literature data. A total of 35 publications, published between 1948 and 2023, were analyzed. From these, information on 100 finds from 1932–2022 was selected.

Thus, a total of 108 finds were collected (Popova and Popov 2025). The data were divided into three groups according to the time of discovery, corresponding to the three study periods:

1. 1932–1980: 42 findings, two of which were made before 1961 (1932 and 1959).
2. 1981–2000: 8 findings.
3. 2001–2022: 58 findings; after 2020 – 4 findings.

As can be seen, several detection points were outside the analyzed periods. Firstly, we used two *I. pavlovskyi* points dating back to before 1961. One dates back to 1932, the site of the first detection of this species in Primorsky Krai. Several subsequent detections were made in this region between 1961 and 1980 in close proximity to this site (Fig. 1). Therefore, we believe *I. pavlovskyi* could have been detected at this site and during this period. The second detection dates back to 1959 and was made in Dunhua County, Jilin Province, in northeast China. This year practically falls within the 1961–1980 period, and the other nearby detection sites are located in eastern Kazakhstan and also date back to this period (Fig. 1). So, we have reasons to believe that these sites could not have significantly distorted the modeling results.

Furthermore, we used four detection sites after 2020. Three of them were from 2021 and 2022 and are located on islands in the Sea of Japan near Vladivostok (Popov Island and Putyatin Island), where this species had previously been found. The fourth detection point dates back to 2022 and was made in Krasnoyarsky Krai. Given the proximity of this date to the 2001–2020 period, we would not expect significant differences in climatic conditions at that detection point in 2022 compared to the average climate for that period.

To eliminate duplicates and closely located loci, thinning was performed using the spThin package for the R programming environment (Aiello-Lammens et al. 2015). Thinning was performed separately for each of the

¹GBIF Occurrence Download (31 October 2024) DOI: 10.15468/dl.3dgaqu.

three time groups mentioned above, since it is assumed that points with the same or very close coordinates in different periods have different climatic characteristics. The minimum allowed distance between finds was 10 km, as recommended in Radosavljevic and Anderson (2014). All calculations in this study were carried out using scripts in R and Python programming languages.

As a result of thinning, 81 points were obtained (Fig. 1). They were used for further modeling.

In order to reduce the randomness effect in background point generation, independent runs of MaxEnt were performed on 20 pre-created sets of 10,000 background points uniformly generated within a spatial rectangle with coordinates 30°–60° N and 30°–179° E. This region contains all detection points of the studied species and a number of areas in which *I. pavlovskyi* may have potential distribution. The obtained modeling results (rasters with habitat suitability values, predictor importance measures, modeling quality measures, etc.) were averaged.

Climate data

The climate data source used was the CRU TS 4.03 climatological dataset of the University of East Anglia (Harris et al. 2020), which contains monthly resolution meteorological observations interpolated onto a regular spatial grid with a cell size of $0.5^\circ \times 0.5^\circ$.

Based on these data, values of 19 standard bioclimatic parameters (BIO1...BIO19) selected within the WorldClim2 project for eco-climate studies (Fick and Hijmans 2017) and widely used in habitat modeling (Drake and Bossenbroek 2004; Bellard et al. 2013; Stoica 2018; Wang et al. 2023) were calculated. They were calculated based on averaged climate data for 3 twenty-year periods (1961–1980, 1981–2000, 2001–2020) and for the entire sixty-year period (1961–2020). Bioclimatic values at detection points were obtained by linear interpolation, corresponding to the climatic period of each detection.

The values of bioclimatic parameters at the background points were calculated for the period 1961–2020. The aim of generating background points over the full 60-year period was to cover all three analyzed periods. This approach can potentially lead to inconsistencies between two types of the model input data: the detection points, which were divided into and characterized by climate

conditions according to the three periods, and the background points, which were characterized according to a single averaged climate. But we can remember that the problem of “correct” choice of territory and number of background points has not been solved yet, and can result in uncertainty in the constructed models. Nevertheless, all these potential problems can be largely solved by accurate model parametrization and the use of appropriate model quality metrics.

A Python 3 module for the calculation of bioclimatic parameters is available in the repository².

Selection of bioclimatic parameters and parameters of modeling

Modeling of the territory of possible distribution of *I. pavlovskyi* was carried out using the MaxEnt algorithm, software version 3.4.1. A common practice when using MaxEnt is to take measures to reduce collinearity among predictors (Elith et al. 2010b). There are different approaches to achieve this goal (Dormann et al. 2012). In this work, a method of selecting a parameter set with minimal correlation was used. This method was described in greater detail in Popov and Popova (2025). At the first stage, the HDBSCAN algorithm was used to identify correlation groups, i.e., groups of predictors with a significantly higher pairwise correlation than the correlation between members of different groups. The statistic $d = 1 - r$ was used as a measure of distance between samples, where r is the Pearson linear correlation coefficient calculated for the series of bioclimatic parameter values at the grid nodes within the region of background point generation. Six correlation groups were identified. Selection within the groups was carried out on the basis of modeling the range of the studied species for all 19 bioclimatic parameters with an analysis of their significance for constructing the model. The parameter with the highest significance was selected from each group.

The final selection of bioclimatic parameters was carried out together with the selection of features – transformation functions of predictors. Akaike Information Criterion corrected (AICc), Boyce Index (BI) and Area Under Curve (AUC) were used as model quality metrics. A model with the following combination of parameters was selected as the most effective: a set of five bioclimatic parameters

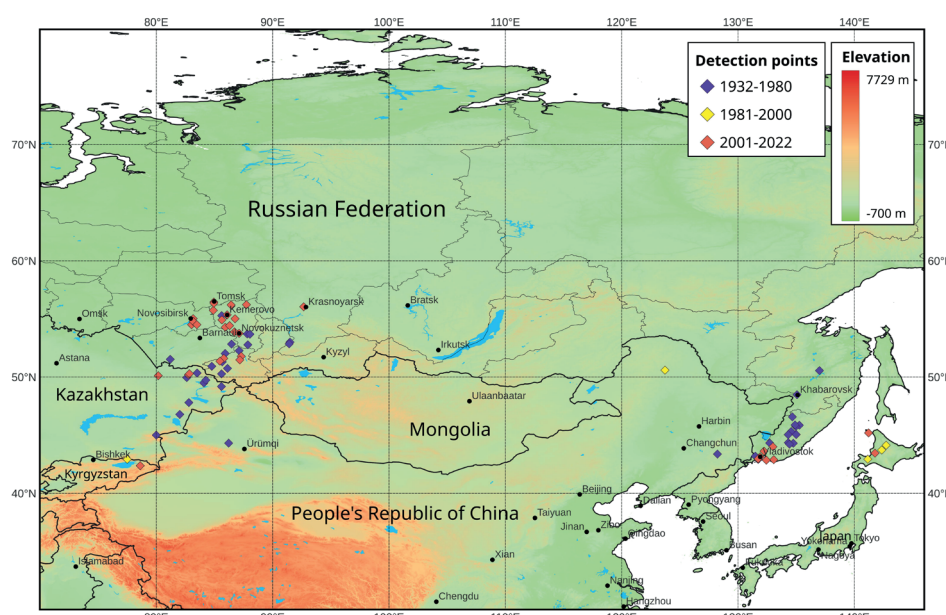


Fig. 1. Spatial distribution of *I. pavlovskyi* detection points used for modeling the distribution of this species

²<https://doi.org/10.5281/zenodo.13913422>

(BIO1, BIO2, BIO4, BIO12, BIO15) and a set of features with linear, quadratic, and product transformation functions.

A detailed description of the model parameter selection process is available in the repository³, in the file Selection_of_model_parameters.pdf.

RESULTS

Fig. 2 shows the modeled potential distribution of *I. pavlovskyi* worldwide for three twenty-year periods of the second half of the 20th and early 21st centuries (1961–1980, 1981–2000, 2001–2020). As can be seen, areas of high suitability for this tick are located in Eurasia and North America.

According to the model (Fig. 2), North America has extensive regions of *I. pavlovskyi* tick potential distribution in the northern United States and much of Canada. Currently there are no known finds of this species on that continent. According to the constructed model, no significant changes were observed in the territory of *I. pavlovskyi*'s potential climatic range in North America for the studied periods, but the western part became somewhat less suitable for the species' habitation in recent decades.

Fig. 3 shows a detailed map of the potential distribution area of *I. pavlovskyi* in Eurasia. In general, as can be seen, most of the detection points are located in areas with high suitability of climatic conditions for tick habitation. Along with them, the model also identifies a number of large areas for the *I. pavlovskyi* possible distribution where this species has not been found to date. According to the constructed model, the main part of the potential distribution area of *I. pavlovskyi* is located in Russia.

As can be seen in Fig. 3, the largest changes occur in the western part of the *I. pavlovskyi* range. A region of possible distribution is identified west of Lake Baikal, in the Irkutsk region. It expands south to the border with Mongolia. The greatest expansion in this region occurs to the east and north of Krasnoyarsk, particularly during the period 2001–2020. Expansion is also observed in the western and northern directions in the area of Novosibirsk, Tomsk, and Kemerovo, which is in good agreement with observations (Grigoryeva and Livanova 2012; Livanova et al. 2016; Mikryukova et al. 2014; Kovalev et al. 2015; Tkachev et al. 2017; Nikoshenko and Zubova 2021). In the southern direction, expansion is expressed in the Republic of Tyva, up to Kyzyl.

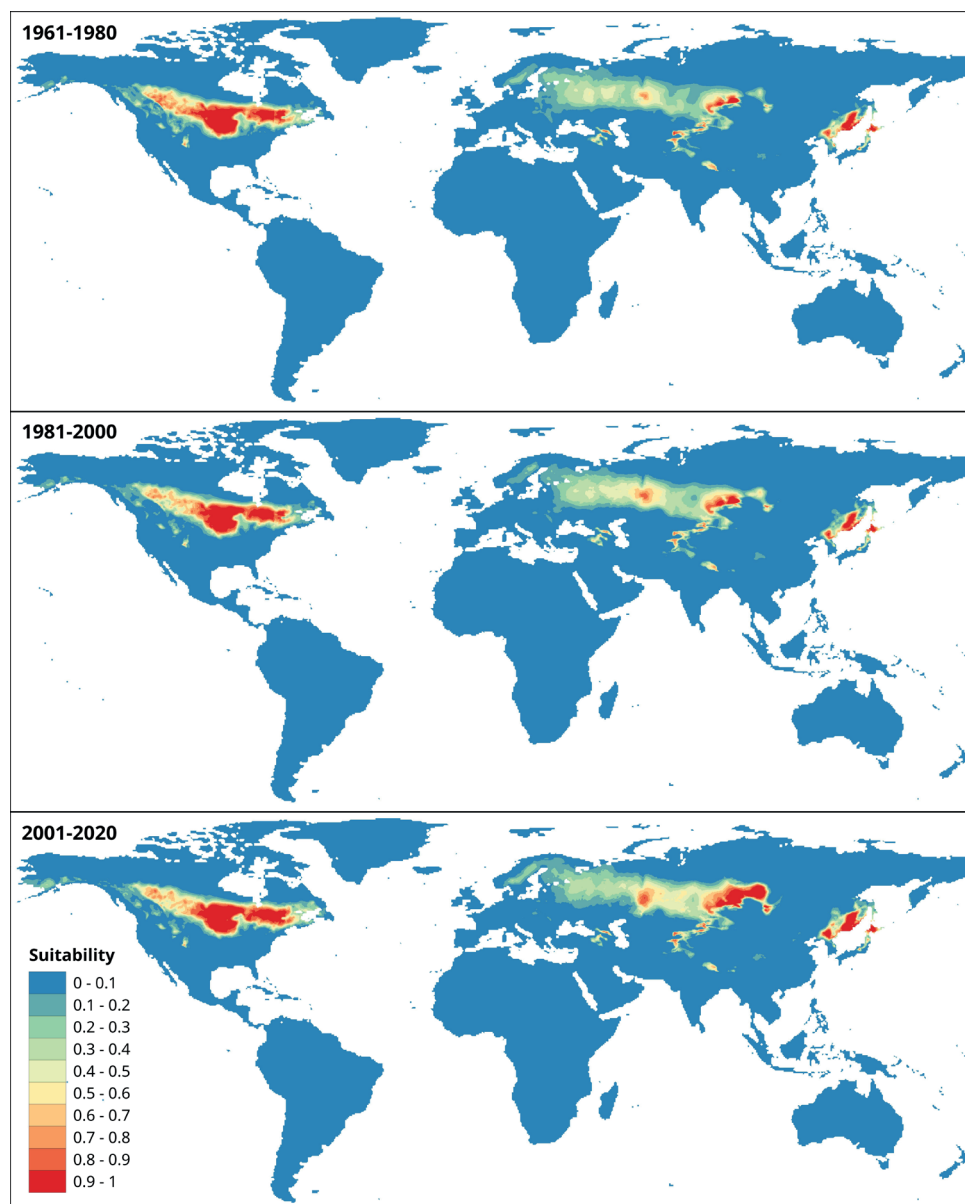


Fig. 2. Geographic distribution of the *I. pavlovskyi* habitat suitability worldwide for three twenty-year study periods from 1961 to 2020 according to the constructed model

³<https://doi.org/10.5281/zenodo.15052161>

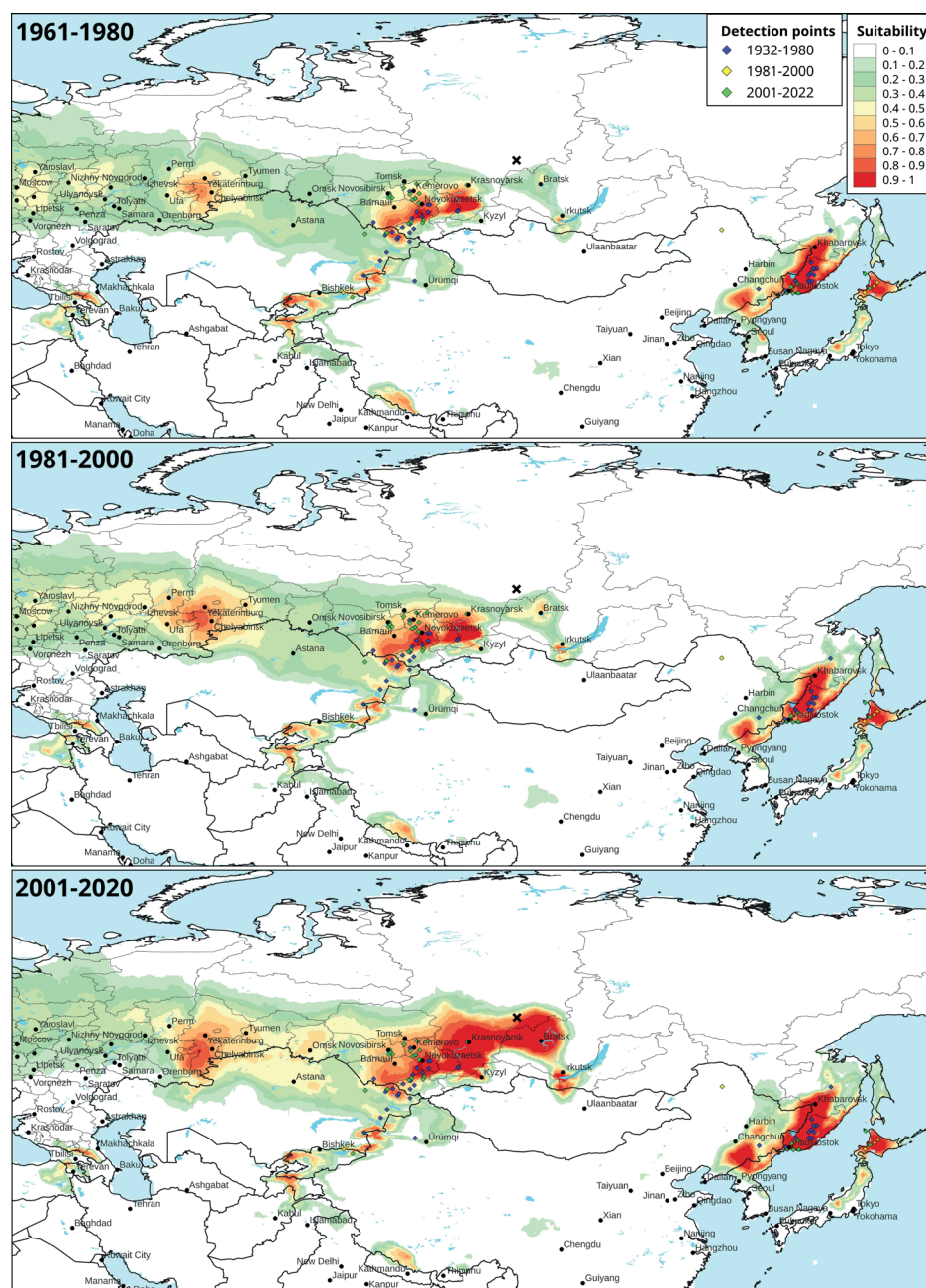


Fig. 3. Geographic distribution of the *I. pavlovskyi* habitat suitability in Eurasia for three twenty-year study periods from 1961 to 2020 according to the constructed model

An area of *I. pavlovskyi* possible distribution is identified in the southern Urals, for which there are no detection records. By the 2001–2020 period, this area significantly expands to the east and south, practically merging with the southern Siberian area of possible distribution. It includes northern regions of Kazakhstan. Also, areas of potential distribution are identified in the west of Kyrgyzstan and Tajikistan, as well as in the North Caucasus and at the borders of Turkey, Georgia, and Azerbaijan. No significant changes are observed in these areas during the studied periods of time.

In the eastern part of the range, possible distribution areas are identified in the Russian Far East and in Japan on Hokkaido Island. In Japan, a new area is also discovered on Honshu Island. A possible distribution area is also identified in the north of the Korean Peninsula and in eastern China. No significant changes in the territories of *I. pavlovskyi* possible distribution in these regions are observed, with the exception of its slight expansion in the Harbin area. A territory of possible distribution, for which there are no

records of detection, is also found in southwestern China, in Tibet, on the border with Nepal.

Assessment of bioclimatic parameter importance for constructing a model of the *I. pavlovskyi* possible distribution was performed using four types of tests provided by MaxEnt software. The most important parameter was BIO1 (annual mean temperature), followed by BIO15 (precipitation seasonality), BIO12 (annual precipitation), and BIO4 (temperature seasonality). The least important parameter was BIO2 (mean diurnal temperature range).

A more detailed analysis of the obtained results is available in the repository⁴, in the file *Additions_to_Results_and_Discussion.pdf*.

DISCUSSION

We calculated and mapped the values of the MESS metrics and standard deviation of suitability modeled for the launches of the model on twenty sets of the

⁴<https://doi.org/10.5281/zenodo.15052161>

background points. MESS (Multivariate Environmental Similarity Surfaces; Elith et al. 2010a) allows estimating the possibility of transferring the modeling results to new territories beyond the observed species ranges. It was established that MESS indicates the correctness of the conclusions about the potential distribution of *I. pavlovskyi* on all new modeled areas, including North America. The standard deviation allows one to assess the uncertainty in modeling results. It did not exceed the value of 0.1, indicating a low level of uncertainty in our model. Maps of these metrics are available in the repository⁵, in the file *Additions_to_Results_and_Discussion.pdf*.

The constructed model of the *I. pavlovskyi* range successfully identified the known distribution regions of this species in the Far East, Western Siberia, the Republic of Khakassia, Japan, and the eastern regions of Kazakhstan and Kyrgyzstan. In addition, high habitat suitability areas for this species were identified in territories where this species is currently not found. Some of these areas are adjacent to areas with already recorded habitat of the species, while other areas are located quite far from them.

According to the obtained results, the *I. pavlovskyi* tick has little potential for spreading in China. The largest area of its potential distribution is in the northeast. Obviously, further efforts are needed to study the actual distribution of this species in China.

The constructed model showed a vast territory of potential habitat for *I. pavlovskyi* in North America. Whether *I. pavlovskyi* could realistically invade this continent remains a debatable issue. For example, studies have shown a fairly high invasive potential of the North American species *I. scapularis* in Eurasia, but to date this species has not been found on Eurasian continent despite active transport links and numerous invasions of other species (Zhang et al. 2022). The possibility of this tick species' invasion onto the North American continent is a topic worthy of separate study and requires further research.

The modeling provided informative data on changes in the *I. pavlovskyi* tick potential range over the three study periods (1961 to 2020), which are associated with the observed climate changes. The greatest changes were found in the northwestern part of the tick's range – on the territory of Siberia in the Russian Federation. Here, a significant expansion of the potential distribution area of *I. pavlovskyi* in the 21st century was noted. The expansion occurs mainly in the western, northwestern, northern, northeastern, and especially eastern directions. According to the constructed model, these changes may result in the formation of a single habitat of the *I. pavlovskyi* species from the Ural to Lake Baikal.

According to our model, the *I. pavlovskyi* discovery point in the Krasnoyarsk Territory at 59.04° N, 98.67° E, dating back to 2005 and originating from GenBank (marked with 'x' in Fig. 3), falls within the range of relatively high suitability (0.6–0.7) in the period 2001–2020. During the selection stage, this point was discarded as an erroneous or accidental introduction, since it was located at a large distance from other discovery points. However, our model confirmed the realism of the information about this discovery. Thus, this fact can also serve as confirmation of the ongoing significant expansion of the *I. pavlovskyi* range far to the northeast of its known Siberian habitat, which is a consequence of the observed climate changes in this region.

In other more southern areas of the *I. pavlovskyi* range (the Far East, Central and East Asia), the boundaries and degree of climatic condition suitability of potential areas for the possible tick spread remain virtually unchanged over time and are similar for all three periods studied.

The parameter BIO1 (annual mean temperature) had the greatest importance by a substantial margin compared to other parameters. Previous studies have shown the high importance of average annual temperatures for the formation of populations of *I. ricinus* and *I. persulcatus* ticks, related to *I. pavlovskyi* (Sirotkin and Korenberg 2022).

CONCLUSIONS

As a result of the conducted research, a model of the climatic range of the tick *I. pavlovskyi* was constructed using the MaxEnt algorithm for three periods (1961–1980, 1981–2000 and 2001–2020). Areas of *I. pavlovskyi* potential distribution all over the globe, including regions where actual findings are absent, were identified. It was demonstrated that the greatest changes occur in the western part of the *I. pavlovskyi* climatic range in Eurasia. The model shows that the observed shifts in the distribution are likely related to observed climate changes. It was demonstrated that annual mean temperature was of the greatest importance for the model construction. These results can be related to the physiological and ecological properties of this species, but the mechanisms underlying these relationships warrant further investigation.

The results obtained are of great importance for public health protection, veterinary medicine, and livestock farming. They can be used for ecological monitoring, adaptation measures, and prevention of the adverse consequences of this species' expansion.

The constructed model can also be used to project and estimate possible future shifts in the *I. pavlovskyi* range under future climate conditions. ■

⁵<https://doi.org/10.5281/zenodo.15052161>

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CHANGES IN ANNUAL RIVER FLOW IN THE VOLGA–KAMA AND ANGARA–YENISEI RESERVOIR BASINS UNDER CONTEMPORARY AND SCENARIO GLOBAL WARMING

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ABSTRACT. The paper presents a study of annual runoff and water availability changes in the Volga–Kama and Angara–Yenisei reservoir basins under contemporary and mid-21st century scenario global anthropogenic warming. The estimates of changes are based on a comparison of runoff under global warming and for the reference period, calculated from observational data and averaged results of its calculation performed with an ensemble of global climate models. During the period of contemporary global warming, the average long-term annual runoff and water availability per unit area and per capita increased, especially in the Volga–Kama reservoir basins, with the exception of the Volgograd reservoir basin, where they decreased sharply. The observed and average model annual runoff in the considered reservoir basins is closely correlated for contemporary global warming as well as for baseline periods. However, for a fairly significant number of basins, the model runoff differs significantly from the observed value. The observed and model difference in the runoff of the two compared periods differs significantly in the Volga–Kama as well as in Angara–Yenisei reservoir basins. Nevertheless, the sign of the difference is the same in almost all basins. In 2040–2069 the annual runoff under varying intensity warming scenarios may increase relative to the model reference period runoff in all reservoir basins of the Angara–Yenisei cascade, whereas in the Volga–Kama reservoir basins the probable runoff changes are likely to have different signs relative to the runoff of the reference period. In most basins the per capita scenario water availability is likely to increase by varying degrees, partly owing to the probable population decline.

KEYWORDS: Volga–Kama and Angara–Yenisei reservoir basins, river runoff, specific water availability, contemporary and scenario global warming, global climate models

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INTRODUCTION

The problem of assessing changes in runoff in reservoir basins in Russia during the period of modern and scenario global warming have received significantly less attention than changes in river basins.

In recent years, results have been published relating to the assessment of changes in runoff formed in reservoir basins during the period of modern global warming and in the baseline period preceding it. Among them, we note the work carried out at the State Hydrological Institute of Roshydromet of the Russian Federation (Georgievskii 2017), in which, based on the summation of observed runoff data and the river analogue method, long-term series of annual and seasonal runoff were obtained for the catchment areas of the main reservoirs of Russia. For the basins of a number of reservoirs, for these purposes, the method of

transforming annual hydrographs of daily water discharges was also used, based on a linear model describing the relationship between water discharges at the inlet and outlet of the calculated section of the river, based on the Kalinin–Milyukov method (Kalinin and Milyukov 1958; Georgievskii and Moiseenkov 1994; Shiklomanov et al. 2011; Milyukova et al. 2020; Yang and Kane 2021; Georgiadi et al. 2023, 2024). Runoff in the Irkutsk Reservoir basin has also been estimated using the regression relationship between the average monthly runoff of the Angara and the average monthly water levels of Lake Baikal, reconstructed using the water balance method, for the period after the commissioning of the Irkutsk Reservoir (Sinyukovich et al. 2024).

A number of studies are devoted to the problem of choosing the boundaries of the base period as a basis for obtaining comparable results of calculations of changes in

runoff under both modern and scenario global warming conditions (Georgiadi and Kashutina 2014, 2016; Georgiadi and Milyukova 2023), as well as the issue of regional binding of the boundaries of the base period and the period of modern global warming (Georgiadi and Kashutina 2014, 2016; Frolova et al. 2022; Georgiadi and Milyukova 2023; Shpakova and Wang 2023). Studies were carried out on the relationship between the boundaries of these periods and the boundaries of long-term phases of increased/decreased runoff, which are among the main features of its long-term changes (Georgiadi and Milyukova 2023; Georgiadi et al. 2023).

Considerable attention is paid to the issue of assessing the quality of simulation of observed hydroclimatic characteristics in river basins using the data of calculation performed on an ensemble of global climate models (Mokhov et al. 2003; Katsov and Govorkova 2013; Georgievsky and Golovanov 2015, 2019; Hai Guo et al. 2022; Georgiadi et al. 2024).

The main objective of the study was to identify the features of changes in annual river runoff and specific water availability for the population and territory under conditions of modern and scenario global warming in the basins of the main Volga–Kama and Angara–Yenisei reservoirs. The study is based on data on annual river runoff formed in the reservoir basins (the so-called local runoff), calculated on the basis of observations and calculations performed on the ensemble of global climate models of the CMIP6 project. One of the important tasks was to assess the quality of simulation of the observed runoff by global climate models.

MATERIALS AND METHODS

Study objects

The objects of the study are the local reservoir basins of the Volga–Kama and Angara–Yenisei reservoir cascades, most of which were constructed between the 1950s and 1980s (Fig. 1) (Barabanova 2004). The local reservoir basins are considered, the boundaries of which are limited by the dams of neighboring reservoirs.

According to hydrological zoning (Kuzin 1960; Kuzin and Babkin 1979), in most of the Volga basin, rivers characterized by spring snowmelt floods, rain floods during the warm season, and low-water periods predominate. The ratio of runoff in the main hydrological seasons of the year changes in the sublatitudinal direction, as well as from the west to the east.

At the same time, in the Yenisei and Angara basins, the main source of runoff formation is rain floods, typical for the entire warm period, the volume of which exceeds the volume of snowmelt flood runoff, and in the winter season there is a low runoff, which is formed due to underground recharge. The Angara runoff, especially at its source, is regulated by Lake Baikal.

In recent decades, there have been significant changes in the annual flow of rivers in Northern Eurasia and their intra-annual distribution (Shiklomanov 2008; Georgiadi et al. 2014; Georgievskii 2017; Frolova et al. 2022; Georgiadi et al. 2024).

The flow of the Volga and Kama, Yenisei and Angara rivers, especially before their confluence, is regulated by large reservoirs. The total volume of the main Volga–Kama reservoirs is 168 km³, and that of the Angara–Yenisei is 393 km³ (Barabanova 2004).



Ivan'kovo (basin area 41×103 km²), (2) Uglich (19×103 km²), (3) Rybinsk (66×103 km²), (4) Gor'ky (77×103 km²), (5) Cheboksary (374×103 km²), (6) Kama (165×103 km²), (7) Votkinsk (16×103 km²), (8) Nizhnekamsk (187×103 km²), (9) Kuibyshev (234×103 km²), (10) Saratov (78×103 km²), (11) Volgograd (67×103 km²), (12) Sayano-Shushenskoe (185×103 km²), (13) Krasnoyarsk (106×103 km²), (14) Irkutsk (542×103 km²), (15) Ust'-Ilimsk (49×103 km²), (16) Bratsk (158×103 km²), (17) Boguchany (44×103 km²)

Fig. 1. Map of catchment areas of the Volga–Kama and Angara–Yenisei reservoirs

DATA

Period of instrumental observations

Annual runoff calculated based on observation data

The study used data on annual runoff formed in reservoir catchment areas, averaged over the period of modern global warming and the baseline period, which are discussed in more detail in the Methods section.

The results of calculations for the period 1946–2013 were used as the source data on the annual flow (inflow to reservoirs), which is formed in their local catchment areas. They are based on the runoff summation method for rivers flowing into reservoirs and the river analogue method (Georgievskii 2017). In this approach, for a part of the territory of the reservoir basin, the available observed data are calculated by summing up the river discharges determined at the outlet gages. To calculate the inflow from the catchment area not covered by hydrometric observations, the method of hydrological analogy is used, the essence of which consists of transferring hydrometric data of the studied rivers (analog rivers) to an area where observations of river runoff are not carried out.

The average long-term annual runoff calculated in this way for the period 1978–2013 served as its estimate for the period of contemporary global warming (PCGW), and for the period 1946–1977 it was used as the reference period (RP) runoff. Since in our model runoff calculations we use the periods of the 1931–1980 and 1981–2010 as the RP and PCGW, respectively, it was necessary to assess how significantly the differences in the boundaries and duration of the above periods affect the average long-term runoff. Since the Georgievskii (2017) provides runoff only for 1946–1977 and 1978–2013, we carried out such a comparison for catchment areas of a number of reservoirs (Table 1), for which long-term series of reconstructed water flows were obtained based on the method of transforming annual hydrographs of daily water discharges (Milyukova et al. 2020; Georgiadi et al. 2024) and based on the regression relationship between the average monthly flow of the Angara and the levels of Lake Baikal, obtained from data for the period before the filling of the Irkutsk Reservoir. The water levels of Baikal were reconstructed using the lake water balance method (Sinyukovich et al. 2024). Comparison of the runoff of each period with different boundaries showed that the differences in the average annual runoff in these periods are insignificant (Table 1) (Georgievskii 2017; Milyukova et al. 2020; Georgiadi et al. 2024). At the same time, the average runoff for the periods

1946–1977 and 1978–2013 for the basins of the Krasnoyarsk and Irkutsk reservoirs, determined on the basis of the two considered methods, may differ from each other. The difference in this case is several percent, although for the Krasnoyarsk reservoir basin it reaches 9%.

Annual runoff calculated using an ensemble of global climate models

The annual runoff data from the IPCC CMIP6 project were obtained by its calculations in specially developed blocks of global climate models. The main calculation schemes of river flow performed on an ensemble of global climate models are analyzed in (Georgievsky and Golovanov 2015, 2019). The annual runoff data were calculated by using the daily water discharges obtained under the IPCC CMIP6 project¹ (Eyring et al. 2016; O'Neill et al. 2016) for each of the 19 global climate models (GCMs) for the so-called “historical” period (1850–2014). Data from a list of global climate models of relatively high spatial resolution, which are used for scenario forecasts in the Climate Center of Roshydromet of Russia², were used. The initial daily runoff data were averaged for each year and interpolated using the bilinear interpolation method into the nodes of a uniform grid of 0.5 degrees in latitude and longitude. The data were averaged for the periods 1931–1980 (base period), 1981–2010 (the period of modern global warming), and for the territory of the reservoir basins considered.

The period of the mid-21st century global warming scenario

The initial data were the daily runoff calculated on the ensemble of global climate models (discussed above), obtained for the period 2015–2100 under three scenarios: the least intense warming (SSP 1-2.6), moderate warming (SSP 2-4.5), and the most intense warming (SSP 5-8.5). The study used data on annual runoff averaged for the period 2040–2069 and for the territory of the reservoir basins under consideration.

METHODS

Approach to assessing changes

The approach to assessing changes in runoff during both the modern and scenario (anthropogenic) global warming periods is based on the method of comparing

Table 1. Comparison of the average long-term annual runoff (km³), calculated by the method of summing up river runoff and the method of transforming the annual hydrograph

Reservoir basin	River flow summation method		Method of transformation of annual hydrograph			
	1946–1977	1978–2013	1946–1977	1978–2013	1936–1980	1981–2010
Kama	52.4	57.2	51	57.8	50.26	57.45
Sayano-Shushenskoe	47.5	48.5	47.5	48.7	47.6	48.8
Krasnoyarsk	42.1	42.8	45.9	45.8	46	47
Irkutsk	61.4	62.6	64*	65.6*	65.2*	68.3*

*Calculations were carried out based on regression relationships between the average monthly flow of the Angara and the average monthly levels of Lake Baikal (Sinyukovich et al. 2024).

¹ESGF MetaGrid (2025). [online] Available at: <https://esgf-metagrid.cloud.dkrz.de/search/cmip6-dkrz/> [Accessed 26 Aug. 2025].

²Roshydromet Climate Center (2025). Official Website. [online] Available at: <https://cc.voeikovmgo.ru/ru/> [Accessed 26 Aug. 2025]

the runoff averaged over these periods with the runoff of the same base period. Such a comparison for the period of instrumental observations is carried out on the basis of runoff estimates for the above periods, calculated both on the basis of observational data and on the basis of data obtained on an ensemble of global climate models. In this case, for the period of instrumental observations, the results of runoff calculations for each of the periods and the difference in runoff between them, obtained both on the basis of observation data and results of calculations carried out on an ensemble of global climate models, are compared.

About the base period

Since the late 1970s–early 1980s, a period of global warming has begun, characterized for the territory of Russia by a significant increase in air temperature and less noticeable changes in atmospheric precipitation compared to the previous multiyear base period. They led to corresponding changes in the characteristics of river runoff. The boundary between these periods is somewhat different in different regions of Russia (Georgiadi et al. 2014, 2023, 2024; Georgiadi and Kashutina 2014, 2016; Frolova et al. 2022; Shpakova and Wang 2023). The period from the 1930s–1940s to the late 1970s–early 1980s is typically used as the base period for calculating climatological norms of river flow in Russia. The period starting from the above years and continuing until recent years is considered to be the period of modern global warming. Other shorter periods are also used. In this study, the period 1946–1978 served as an estimate of the average long-term runoff of the base period, and for the period of modern global warming we use the period 1979–2013 (Georgievskii 2017). See the Data section for more information.

An important issue of the correct use of the results of calculations of changes in runoff under conditions of modern and scenario (anthropogenic) global warming, performed on an ensemble of global climate models, consists of assessing the quality of reproduction of runoff characteristics (in this case, annual runoff in reservoir catchment areas) based on a comparison of model and observed values.

To do this, the simulated and observed runoff of the base period and the period of modern global warming are compared, as well as the difference in the runoff of these periods, calculated using an ensemble of global climate models and based on observation data.

Assessment of specific water availability in reservoir basins

The availability of water resources of the annual river flow in reservoir catchment areas is assessed using their per capita volume (Koronkevich et al. 2014; Georgiadi et al. 2021). The calculations are based on the 1989 population data (by constituent entities of the Russian Federation)³, which are attributed to the base period, and the 2021 population census data (by municipalities of the Russian Federation)⁴, attributed to the period of modern global warming. It should be noted that both population and the character of its spatial distribution in the regions under consideration in the 1989 and 1979 differed slightly. While

in 2021 the total population has changed slightly, it has decreased significantly over the most part of territory under consideration. Data on the constituent entities of the Russian Federation were used as the scenario population for 2045⁵. The above materials served as the basis for assessing the population by municipalities in the Volga–Kama and Angara–Yenisei reservoir basins. At the same time, the population in the basins for 2021 was calculated based on available data for municipalities. The population estimates for 1989 and the scenario population for 2045 in reservoir basins were based on the estimated population in municipalities. These calculations were based on data on the difference in population in the constituent entities of the Russian Federation relative to its population in 2021 and its use for municipalities of the corresponding constituent entity of the Russian Federation. The calculations of the actual and scenario population for reservoir catchment areas were carried out using GIS technologies.

Water availability per capita was compared with the availability of local river runoff resources per unit area of reservoir basins.

RESULTS

Contemporary global warming

Annual runoff in reservoir catchment areas and its changes during the period of contemporary global warming based on observational data Sub-section title

The largest volume of annual runoff, according to Georgievskii (2017), is formed in the basins of the Cheboksary, Kama, Kuibyshev, Sayano-Shushenskoe, Krasnoyarsk, Irkutsk, as well as Nizhnekamsk and Bratsk reservoirs. Their volume is the smallest in the basins of the Ivan'kovo, Uglich, Votkinsk, Saratov, Volgograd, Ust'-Ilimsk, and Boguchany reservoirs (Fig. 2).

During the period of modern global warming, the average long-term annual runoff (see Fig. 2) in the local basins of the considered reservoirs changed quite significantly (according to the calculations given in Georgievskii (2017) relative to the reference period. At the same time, in the basins of all reservoirs (except for the Volgograd Reservoir), the runoff increased, but to varying degrees. In the Volgograd Reservoir basin, there was a sharp (twofold) decrease. The most noticeable increase in runoff (from 10 to more than 20%) was observed in the Volga–Kama reservoir basins, while in the Angara–Yenisei reservoir basins, its growth was much less noticeable (except for the Irkutsk Reservoir, where it increased by about 9%); in the Boguchany Reservoir basin, the runoff even decreased, albeit by only 0.5%.

Specific water availability in reservoir catchment areas and its change in the period of modern global warming

The per capita water availability (Fig. 3a) in the Volga–Kama reservoir basins is considerably lower compared to the Angara–Yenisei reservoir basins, which is explained mainly by the significantly higher population density in the regions of the European part of Russia. At the same time, the specific water availability in the territory (Fig. 3b) in all the considered basins is quite high (with the exception of the Volgograd reservoir basin, located in the steppe zone with its characteristic low

³Population of the USSR: According to the All-Union Population Census 1989 (1990). Moscow: Fin. Stat. (in Russian)

⁴Federal State Statistics Service (2025). Population of the Russian Federation by municipalities as of January 1, 2021. [online] Available at: <https://web.archive.org/web/20211029094621/https://rosstat.gov.ru/compendium/document/13282?print=1> [Accessed 26 Aug. 2025]

⁵Federal State Statistics Service (2025). Estimated Population of the Russian Federation up to 2045 [online] Available at: <https://rosstat.gov.ru/compendium/document/13285> [Accessed 26 Aug. 2025]

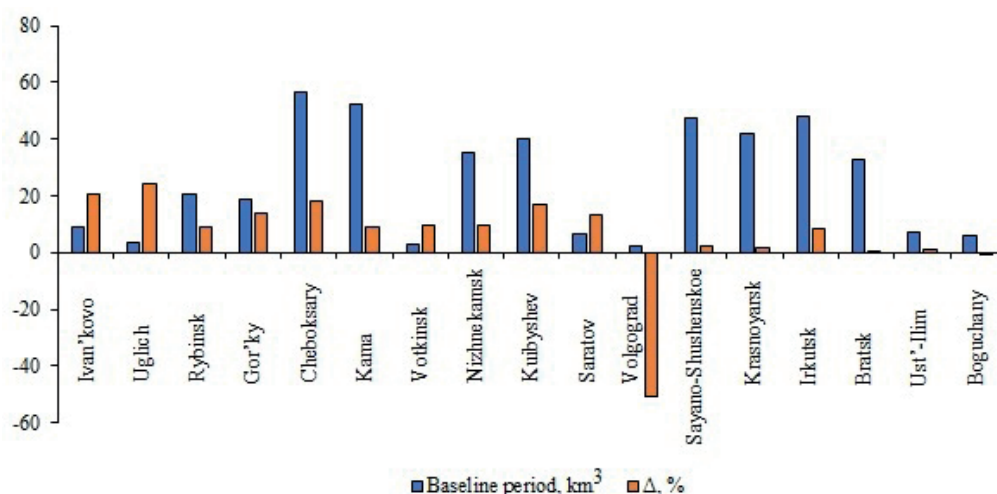


Fig. 2. Average long-term annual runoff in reservoir catchment areas in the base period and its changes during the period of modern global warming, calculated on the basis of observational data

precipitation). The same factors explain the relatively low specific water availability in the Saratov and Irkutsk reservoir basins. The distribution of the volumes of annual runoff and specific water availability per unit area (km²) by reservoir basins has very similar features (Figs. 2, 3b). However, the character of the distribution of water availability per capita over the basins is significantly influenced by the size of the population, which is more influenced by socioeconomic and historical factors (Figs. 2, 3a).

For most of the basins of the Volga-Kama and Angara-Yenisei reservoirs, a relatively close relationship is revealed between these two specific indicators (Fig. 4a, b), although in each of the regions, data for one of the basins (the basins of the Gor'ky and Sayano-Shushenskoe reservoirs) deviate significantly from the average line of relationship, which can be explained by the anomalous combination of these specific indicators of water availability.

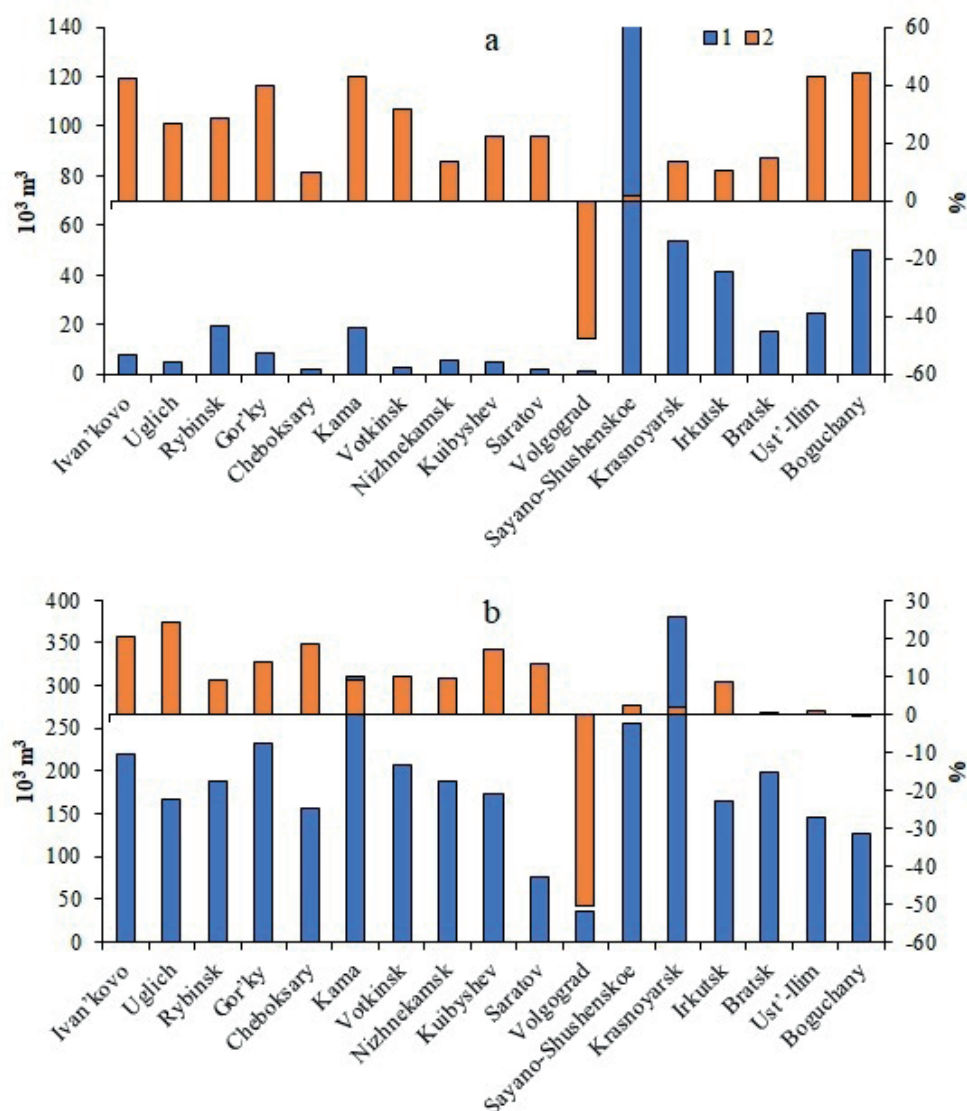


Fig. 3. Water availability due to annual runoff to (a) the population and (b) territory in reservoir catchment areas (1) in the base period and (2) its relative changes (in %) during the period of modern global warming

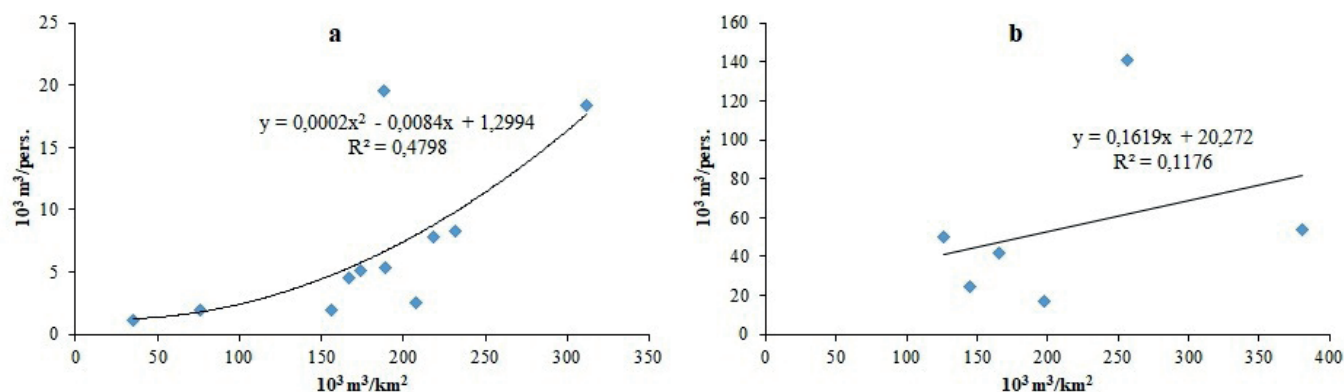


Fig. 4. Relationships between water availability, average long-term annual runoff per capita, and per unit area in (a) the Volga-Kama and (b) Angara-Yenisei reservoir basins, based on base period data

The above also applies to the peculiarities of changes in the specific water availability for the population and territory in the basins of the considered reservoirs during the period of modern global warming. The character of changes in the specific water supply of the territory of reservoir catchment areas is to a certain extent similar to changes in the annual runoff. On the other hand, the per capita water supply changes were greatly influenced by long-term population multidirectional trends in the period from 1989 to 2021. In the overwhelming majority of basins, it decreased and, in most of them, significantly (by 20–30% and more). Only in the Cheboksary Reservoir basin did the population increase (by 7.5%).

Quality of simulation of annual runoff and its changes during the period of modern global warming by ensemble-averaged data of global climate modeling

In this case, the model and observed runoff of the base period and the period of modern global warming are compared, as well as the difference in the runoff of these periods, calculated using an ensemble of global climate models and based on observation data.

It should be noted that the annual runoff for the considered basins of the Volga-Kama and Angara-Yenisei reservoirs, obtained by averaging the results of calculations carried out on an ensemble of global climate models and calculated from observation data, correlate very closely with each other (Fig. 5). At the same time, for a fairly significant number of the basins of the considered reservoirs (especially for Volga-Kama reservoir basins), the model runoff differs significantly from the observed one.

A comparison of the annual runoff calculated based on observational data and the model runoff calculated by averaging the results of calculations performed on an ensemble of global climate models (GCMs) under the CMIP6 program shows that for both the period of modern

global warming and the baseline period, the model runoff overestimates the observed annual local runoff in most of the Volga-Kama reservoir basins and underestimates it in most of the Angara-Yenisei reservoir basins (Fig. 6). Only in two Volga-Kama reservoir basins was it lower for the baseline period (in the Kama and Nizhnekamsk reservoirs) and in one (Kama) for the period of modern global warming. Among the basins of the Angara-Yenisei reservoirs, only in the basin of the Irkutsk Reservoir and only during the period of modern global warming did the model runoff exceed the observed one.

The difference between the model and observed annual runoff varied in the Volga-Kama reservoir basins from almost zero values (Gor'ky Reservoir basin) to 3–6 times (Volgograd Reservoir basin). In the Angara-Yenisei reservoir basins, this difference changes in a narrower range: from values close to zero (Irkutsk, Bratsk and Boguchany (for BP) reservoir basins) to 32% (Krasnoyarsk Reservoir basin). In general, we note that, as a rule, the difference between the model and observed runoff in both the Volga-Kama and Angara-Yenisei reservoir basins during the period of modern global warming is less than in the baseline period (except for the Kama, Nizhnekamsk, and Boguchany reservoirs).

Now let us compare the changes in annual runoff in reservoir catchment areas during the period of modern global warming relative to the base period calculated using the CMIP6 GCM ensemble and their observation data.

The direction of relative changes in the model annual runoff, averaged over the CMIP6 GCM ensemble, during the period of modern global warming and the observed annual runoff relative to the baseline period (in percent of the annual runoff of the baseline period) coincide in most of the considered basins (Fig. 7). The exception is the Saratov Reservoir basin, in which, under the conditions of the PCGW, the model and observed changes occurred in different directions. Note that in the basins of all other

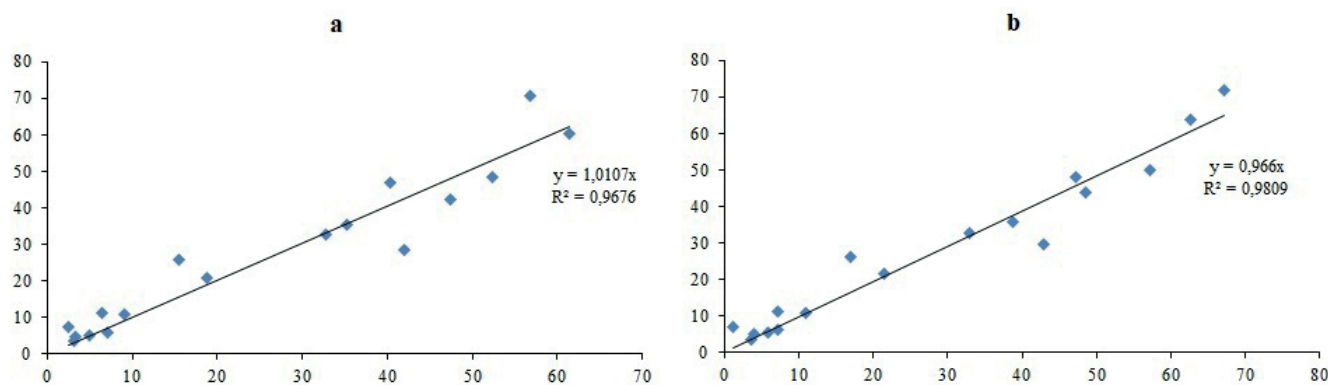


Fig. 5. Regression relationships of annual runoff (km³) in (a) RP and in (b) PCGW, calculated from observational data (ordinate axis) and from global climate models of the CMIP6 project (abscissa axis)

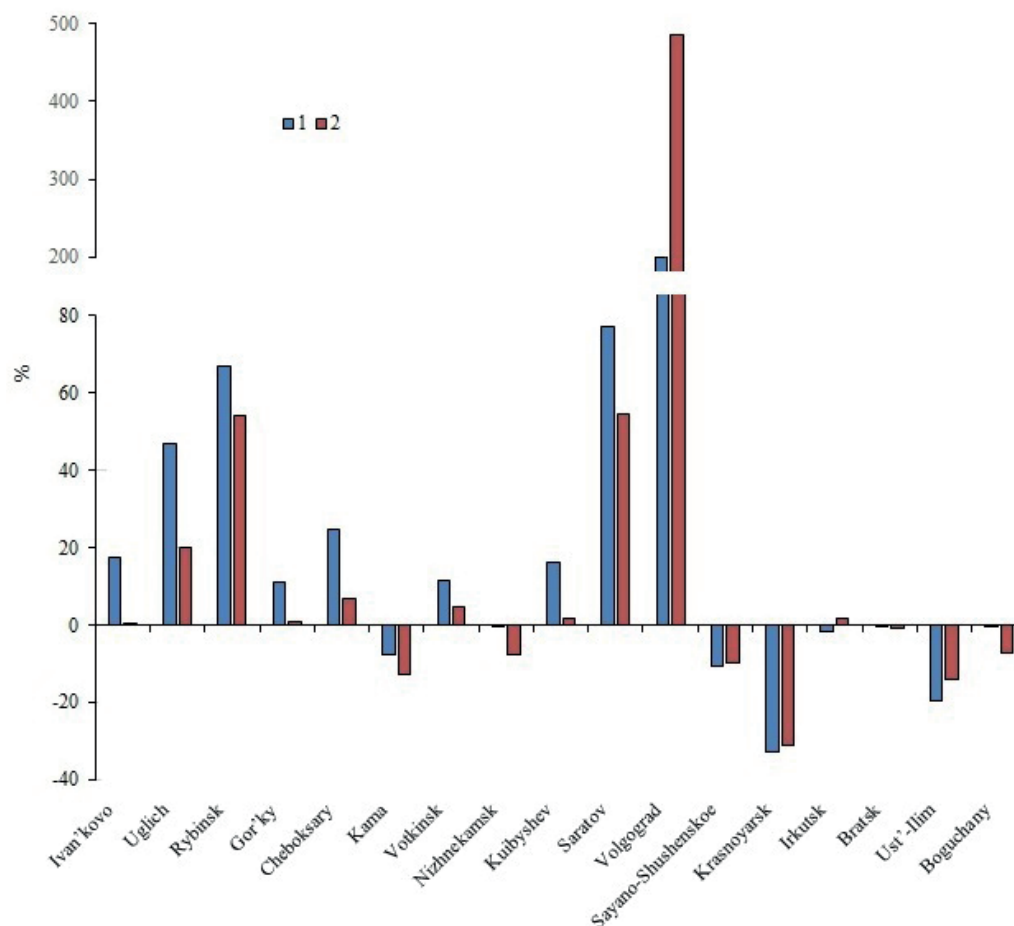


Fig. 6. Difference (in %) between the model (averaged over the ensemble of global climate models of the CMIP6 project) and the annual runoff calculated based on observational data in (1) the baseline period and (2) the period of modern global warming

reservoirs, the model and observed changes in the PCGW were directed toward a decrease in runoff, except for the Volgograd Reservoir basin, where the runoff decreased. The increase in observed runoff was more significant in the Volga–Kama reservoir basins, as well as in the Boguchany and Bratsk reservoirs (in which the changes were barely noticeable). In the basins of other Angara–Yenisei reservoirs, on the contrary, the model increase was greater than the observed one.

In a single basin (the Volgograd Reservoir), the model and observed runoff decreased. Note also that the difference between the model and observed changes was more significant in the Volga–Kama Reservoir basins.

Scenario global warming

Changes in annual runoff

Several groups of basins are identified by the character of changes in the average long-term annual runoff in 2040–2069 relative to the model runoff of the base period under scenario warming of varying intensity (Fig. 8). One of them includes the basins of Angara–Yenisei reservoirs, as well as the Kama and Votkinsk reservoirs. In them, the runoff will probably increase (to varying degrees) under all the considered scenarios of anthropogenic warming. In the basins of another large group of the Volga–Kama reservoirs (Ivan'kovo, Uglich, Rybinsk, Cheboksary, Nizhnekamsk, Kuibyshev, and Saratov), under conditions of the least intense warming, the runoff may increase very slightly (by no more than 5%), whereas under warming of medium and maximum intensity, the runoff will probably decrease. It is only in the Volgograd Reservoir basin that the runoff can decrease under different warming scenarios. In the Gor'ky

Reservoir basin, the runoff will decrease at a low and high warming rate and increase at its medium rate. At the same time, the scale of changes varies within only a few percent.

If we evaluate the changes in runoff in the mid-21st century relative to the model runoff for the period of modern global warming, then the direction of its changes in the Angara–Yenisei reservoir basins and in the Kama reservoir basin will remain the same (Fig. 9), but their scale will decrease. The number of reservoir basins in the second group highlighted above will be reduced to four from among the Volga–Kama reservoirs. The third large group of basins (see Fig. 9) of the Volga–Kama reservoirs (which, when assessing scenario changes in runoff relative to the base period, included only the Volgograd Reservoir basin), in which runoff will probably decrease under scenarios of global warming of varying intensity, may already include six basins, including the Volgograd Reservoir basin.

We next compare the differences in runoff in the reservoir basins under the scenario of warming conditions in 2040–2069 of different intensity with each other. That is, let us compare the difference in runoff between the base period and the ssp 1-2.6 scenario for the following pairs of scenarios: ssp 1-2.6 and ssp 2-4.5, ssp 2-4.5 and ssp 5-8.5 (Fig. 10).

Under the conditions of low-intensity warming, the runoff may increase in the basins of all reservoirs except for the Gor'ky and Volgograd reservoirs (which was already mentioned above). Under conditions of medium-intensity global warming, the runoff in the basins of most reservoirs will probably decrease relative to the runoff under low-intensity warming (except for the Gor'ky and Kama reservoirs). Under the most intense warming (SSP 5-8.5), relative to the runoff during the period of medium-

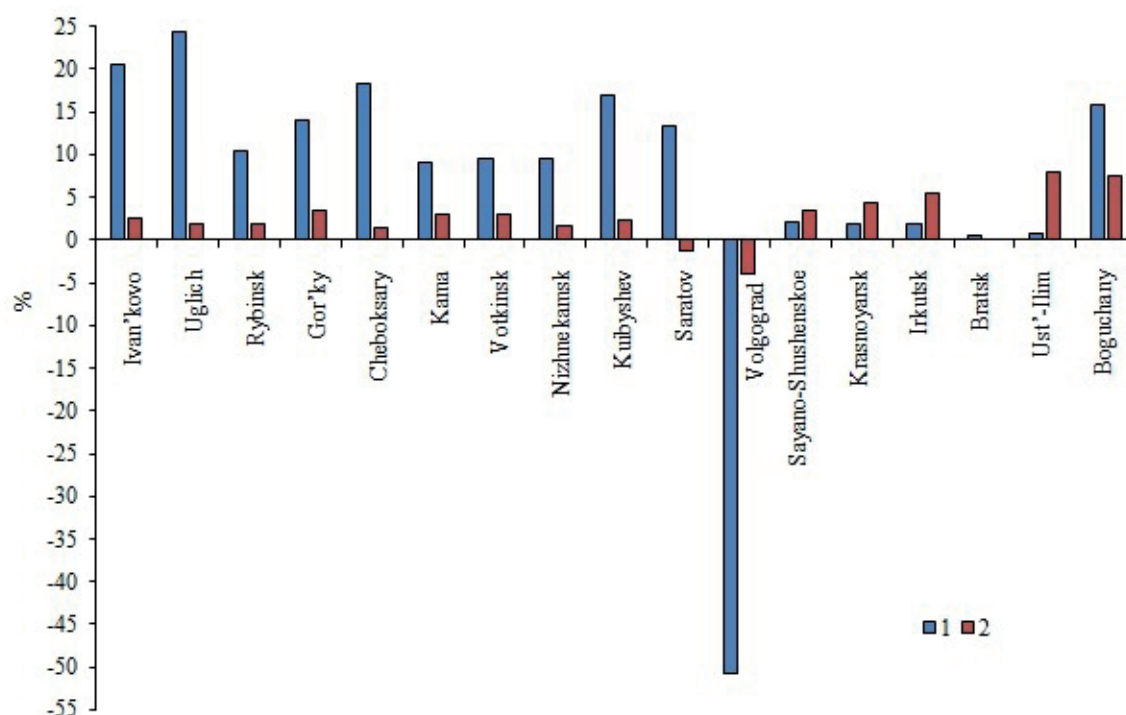


Fig. 7. Difference (in %) between annual runoff in catchment areas of the Volga–Kama and Angara–Yenisei reservoirs during the period of modern global warming and in the baseline period, calculated based on (1) observational data and (2) data averaged over the ensemble of global climate models of the CMIP6 project

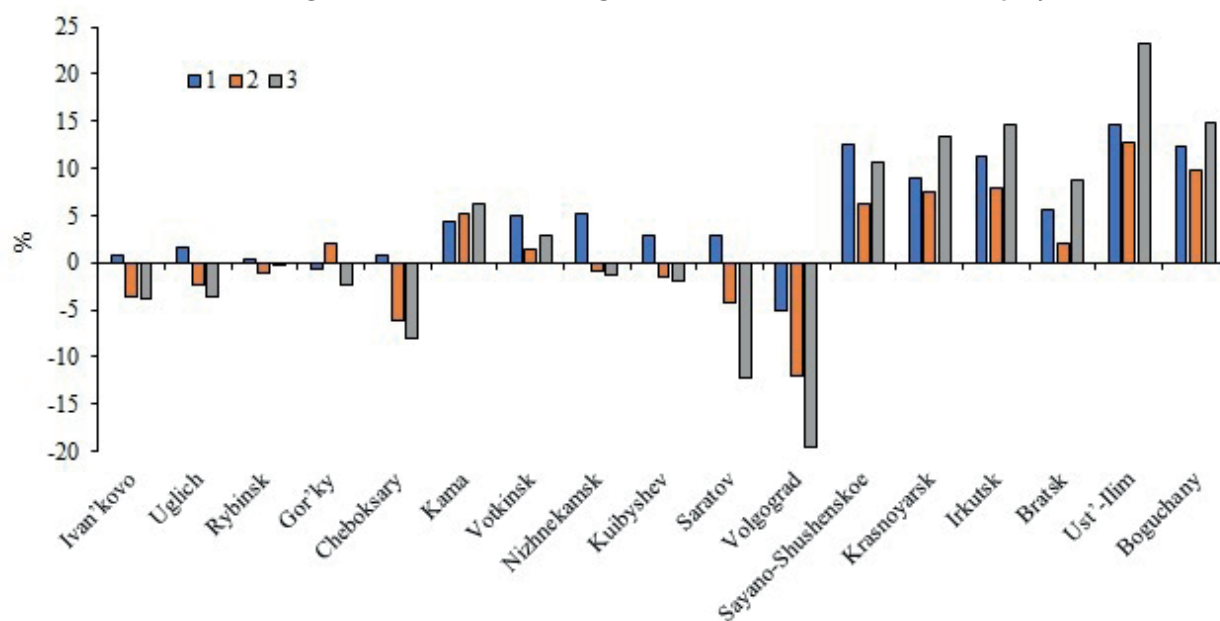


Fig. 8. Changes in annual runoff in 2040–2069 under scenarios (1) SSP 1-2.6, (2) ssp 2-4.5 and (3) ssp 5-8.5 relative to the base-period model runoff

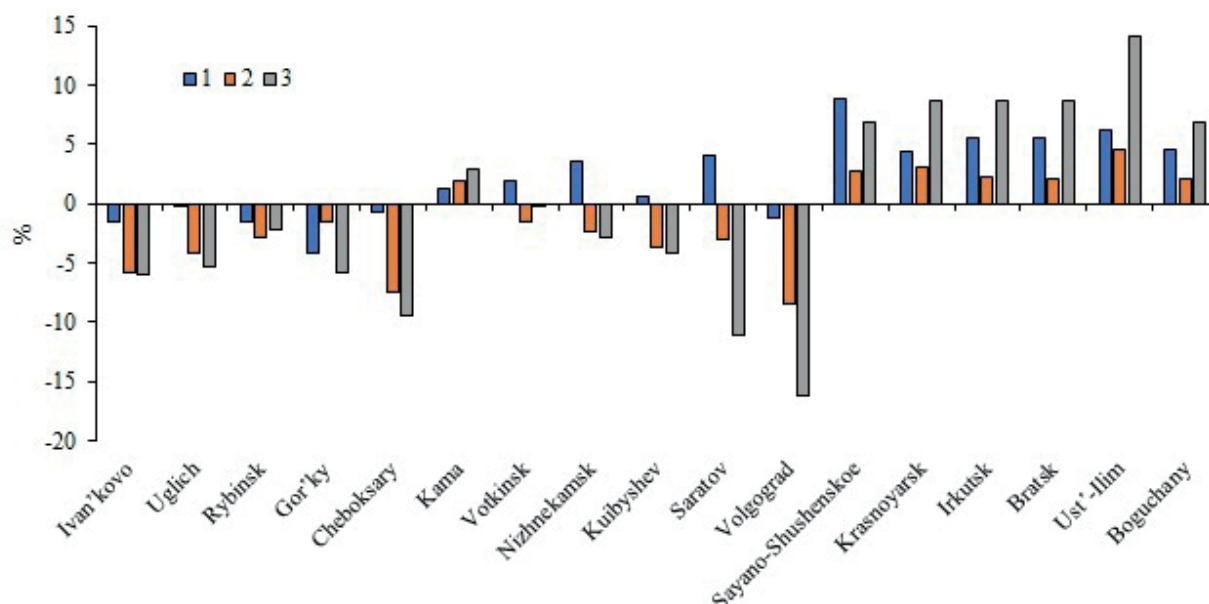


Fig. 9. Changes in annual runoff in 2040–2069 under scenarios (1) ssp 1-2.6, (2) ssp 2-4.5 and (3) ssp 5-8.5 relative to model runoff during modern global warming

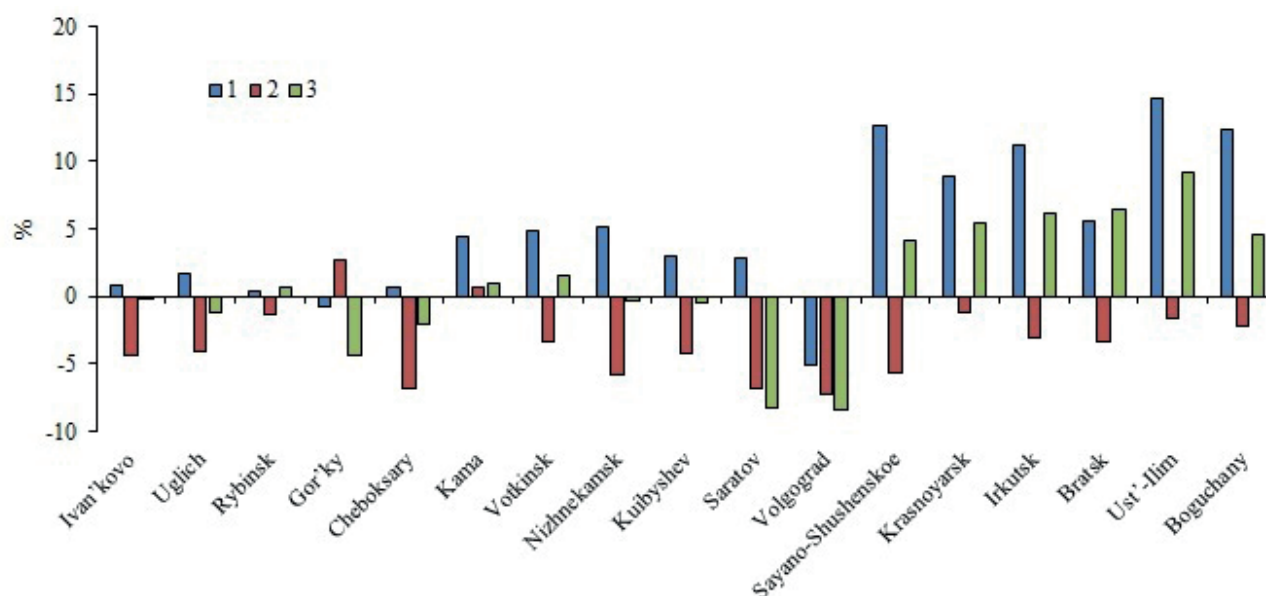


Fig. 10. Changes in the model annual runoff in 2040–2069 under the conditions of: (1) scenario ssp 1-2.6 relative to the runoff of the base period, (2) scenario ssp 2-4.5 relative to the runoff under the conditions of the scenario ssp 1-2.6, (3) scenario ssp 5-8.5 relative to runoff under conditions of scenario ssp 2-4.5

intensity warming, it may increase by 4–9% in the basins of all the Angara–Yenisei reservoirs. In the basins of most of the Volga–Kama reservoirs, it decreases to varying degrees, mostly very insignificantly. Only in the basins of the Gorky, Saratov, and Volgograd reservoirs, the decrease in runoff is comparable to the scale of the possible increase in runoff in the basins of the Angara–Yenisei reservoirs.

Scenario changes in water availability

The character of the scenario changes in water availability per unit area and the volumes of annual runoff in reservoir catchment areas are similar. The character of the scenario changes in per capita water availability in reservoir basins is significantly different, since they are determined not only by changes in annual river flow but also by the population size. Note that under the conditions of all three considered scenarios of varying warming intensity in the basins of most reservoirs, the per capita water availability increases (Fig. 11) and quite significantly (by 10–70%). It

decreases only in three basins (from several to 10%). Note that in the Uglich Reservoir basin, this can occur only under scenarios ssp 2-4.5 and ssp 5-8.5.

DISCUSSION

The results obtained in this study make a certain contribution to improving the understanding of the features of changes in annual runoff under conditions of contemporary and probable future global warming based on observation data and estimates obtained using an ensemble of global climate models.

The obtained estimates of the quality of model calculations of the annual runoff formed in reservoir catchment areas in the period of modern global warming and the baseline period allow us to conclude that global climate models for a number of the considered basins of the Volga–Kama and Angara–Yenisei reservoirs reproduce the long-term averaged annual runoff in the specified periods with acceptable accuracy. At the same time, for the

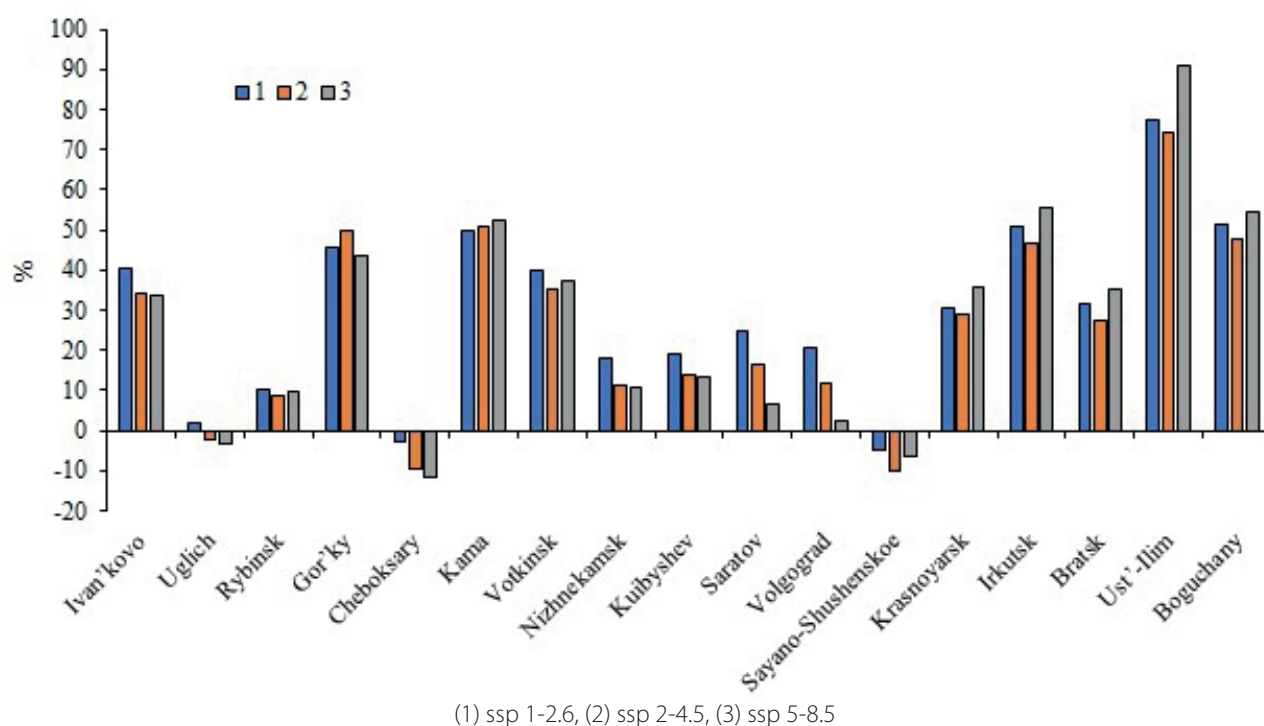


Fig. 11. Scenario changes in per capita water availability relative to the model baseline period

basins of a number of the considered reservoirs (especially for the Volga–Kama reservoirs), the model runoff differs significantly from the observed one, which also is true for model estimates of the difference in runoff during the period of modern global warming and in the baseline period. This is confirmed by other studies (Georgievsky and Golovanov 2015, 2019). All this suggests that estimates of the average long-term annual runoff for a number of regions, obtained by averaging the results of calculations carried out on an ensemble of global climate models, do not adequately estimate the average runoff during the period of modern global warming, the base period, and trends in modern long-term changes in average annual runoff.

To improve the results of runoff change calculations under modern and scenario global warming, it is apparently possible to develop two lines of research. One of them is to take into account regional features of runoff formation to improve the runoff calculation schemes used in global climate models, discussed in (Georgievsky and Golovanov 2015, 2019). Another line of research can be proposed, which involves selecting the best models from the entire available ensemble of global climate models based on a comparison of model results with observational data. It should be noted that such an approach is already being used (Menzhulin et al. 2005; Kislov et al. 2008; Anisimov and Kokorev 2013; Georgiadi et al. 2014; Babina and Georgiadi 2016), but river runoff is usually not used among the compared characteristics. Therefore, when selecting global climate models, it is reasonable to use not only climatic characteristics but also the observed (and most reliably determined) and calculated GCM river runoff for the period of modern global warming and the baseline period and the difference in runoff between these two periods. Also, extremely useful for these purposes is a comparison of observed and calculated long-term runoff series and their statistical characteristics (Motovilov and Gelfan 2019; Hai Guo et al. 2022; Kalugin 2023).

CONCLUSIONS

The study was focused on changes in the annual runoff in catchment areas of the Volga–Kama and Angara–Yenisei reservoirs in periods of modern and scenario global anthropogenic warming in the middle of the 21st century. The assessments of changes are based on a comparison of runoff under conditions of global warming and the base period, calculated on the basis of observational data and on an ensemble of global climate models.

The obtained results are as follows.

1. Comparison of the annual runoff for the period of modern global warming and the base period for the basins of the Kama, Krasnoyarsk, Sayano-Shushenskoe, and Irkutsk reservoirs, calculated by summation and analogy methods (Georgievskii 2017) and the method of calculating daily water discharges for the entire year based on the method of transforming annual hydrographs (Kalinin and Milyukov 1958; Milyukova et al. 2020; Georgiadi et al. 2023, 2024) showed that they give close results.

2. During the period of modern global warming, the average long-term annual runoff (according to calculations based on the methods of runoff summation and analogy given in (Georgievskii 2017)) and the specific water supply for the territory have increased most noticeably in the Volga–Kama reservoir basins, while in the Angara–Yenisei reservoir basins their growth was significantly less noticeable (except for the Irkutsk reservoir).

3. In most basins, the per capita water availability increased not only due to increased runoff but also due to a significant decrease in population (by 20–30% or more) in the period from 1989 to 2021. Only in the Cheboksary Reservoir basin was there a noticeable (7.5%) reverse trend in population change, which affected the corresponding change in the per capita water availability. For most basins of the Volga–Kama and Angara–Yenisei reservoirs, a relatively close relationship is revealed between the specific water availability for the population and the territory.

4. Comparison of the observed annual runoff in reservoir basins, its changes during the period of modern global warming, and its estimates obtained on the basis of averaging the results of calculations carried out on an ensemble of global climate models of relatively high spatial resolution, which are used for scenario forecasts in the Climate Center of Roshydromet of Russia showed that:

–the observed and average model annual runoff in the considered reservoir basins are closely correlated ($R^2 > 0.9$). However, for a fairly significant number of basins, the model runoff differs significantly from the observed value;

–for both the period of modern global warming and the baseline period, the model runoff overestimates the observed annual runoff in most basins of Volga–Kama reservoirs and underestimates it for most of the Angara–Yenisei reservoir basins. At the same time, the difference between them is significantly greater in the Volga–Kama reservoir basins;

–in the basins of all reservoirs, both the observed (except for the Volgograd Reservoir) and model (except for the Saratov and Volgograd reservoirs) runoff during the period of modern global warming increased compared to the baseline period. The increase in the observed runoff was more significant in the basins of the Volga–Kama reservoirs, as well as in the basins of the Boguchany and Bratsk reservoirs (in which the changes were barely noticeable). In the basins of other Angara–Yenisei reservoirs, on the contrary, the model increase in runoff was greater than the observed one. In only one basin (Volgograd Reservoir), both the model and observed runoff decreased quite noticeably.

5. According to the character of changes in annual runoff in 2040–2069 relative to the model runoff of the base period under conditions of scenario warming of varying intensity, two main groups of basins are distinguished. In one of them (which consists of the basins of the Angara–Yenisei, as well as the Kama and Votkinsk reservoirs), the scenario runoff will probably increase to varying degrees under all the considered anthropogenic warming scenarios. In the basins of another group (which includes the Volga–Kama reservoir basins), under the conditions of the least intense warming, the runoff may increase very slightly (by no more than 5%), whereas under warming of medium and maximum intensity, the runoff may decrease. Only in the Volgograd Reservoir basin, under the implementation of different warming scenarios, the runoff will probably decrease quite significantly.

6. The character of scenario changes in the water supply of the territory of reservoir catchment areas both in the base period and in the conditions of modern global warming is in many ways similar to changes in the volumes of annual runoff in these basins. Scenario changes in water availability per capita are characterized by regional features of population change (both in the base period and in the conditions of modern global warming). Under the conditions of all three considered scenarios of different warming intensity in the basins of most reservoirs, water availability per capita may increase and quite significantly (by 10–70%), including in connection with the predicted change in the population. Only in three basins (Uglich, Cheboksary, and Sayano-Shushenskoe) it will probably decrease (from a few to 10%).

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