RESEARCH PAPER

MODELING OF THE 50-YEAR DYNAMICS OF THE RECLAIMED LANDS VULNERABILITY TO WIND SOIL EROSION IN THE REGION OF PRIPYAT POLESYE

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ABSTRACT. Environmentally unsafe agricultural use of soil and land resources is caused by the high share of reclaimed land in the Pripyat Polesye region and global climate change. The research aims to evaluate the long-term vulnerability of the soil cover, utilizing the example of a large agricultural enterprise spanning over 9,200 hectares in a zone of hydro-technically drained peat-bog and alluvial soils in the central and terraced floodplain of the Pripyat River (Belarus). The assessment of the degree of vulnerability is expressed on the basis of the genetic characteristics of soils in accordance with the soil-hydrological constants: the moisture content of the capillary fringe rupture and the limiting field capacity. The dynamics of spatial and temporal changes in soils by groups of vulnerability to wind erosion is controlled in geoinformation software based on specialized spectral brightness indices according to satellite data for plant vegetative season. Dependences of the degree of vulnerability on heterogeneity of soil cover structure and intensity of agricultural use of soils by types of land have been established. The obtained patterns can be used to develop adaptive landscape farming systems in the Polesye region and to forecast degradation processes of agricultural lands.

KEYWORDS: erosion, soil cover, Pripyat Polesye, GIS, TVDI

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INTRODUCTION

Unfavorable meteorological phenomena due to global climate change annually cause significant damage in the most weather-dependent sector of the economy – crop farming. Over the past 50 years, droughts in Belarus have doubled in frequency, leading to wind erosion of soils (Chervan et al. 2022), with the region of drained peat-bog soils – Pripyat Polesye – carrying the greatest risk.

Active reclamation works began in the second half of the 20th century in the Belarusian Polesye territory in the Pripyat River valley, with the goal of regulating the water regime of peat-bog soils for their use in agricultural processes. Land reclamation has led to a significant reduction in the area of natural landscapes, primarily large swamps. Thus the area of swamps before the start of land reclamation in the 1960s (Bakarasov 2015) comprised 2.9 million hectares, or 14.2% of the territory of Belarus. Only 0.7 million hectares out of 2.2 million hectares of all drained lands (~30%) are occupied by ameliorative systems with bilateral regulation of the water regime. It predetermines high environmental risks of wind erosion of automorphic and semi-hydromorphic soils in the zone of influence of the drainage network against the background of global climate change and the close relationship of agroecosystems with meteorological conditions.

Currently, 863 thousand hectares of swamps (29.3% of the original area) have been preserved in Belarus as a result of widespread, often excessive, drainage and extensive extraction of peat in a natural or close to natural state. 630 thousand hectares are located within the boundaries of specially protected natural areas; about 313 thousand hectares require the establishment of a special protection regime; and 314 thousand hectares of swamps have international protection status. Belarus uses more than 2.8 million hectares of drained land (34%) for agricultural purposes in 2021; each administrative region of Belarus accounts for an average of 24.2 thousand hectares, with the Polesye region accounting for even more. The share of drained agricultural landscapes in Polesye exceeds 26% which is almost 3 times more than in the rest of the country (Meerovsky & Filippov 2022).

A number of state programs have been approved to restore disturbed lands in the Belarus providing for cultural and technical measures on sandy and sandy loamy soils left after peat extraction due to the reduction in the area of arable land on drained lands in accordance with the regional measures of the European Union ("Climate change adaption" 2019). However, it necessitates a thorough examination of the natural environment, which is already in a vulnerable state: changes in soil levels, groundwater levels, and soil-forming processes have led to a radical transformation of the main types of vegetation. Sedimentation of alluvial deposits occurs throughout the territory, primarily in the central floodplain against the background of wind erosion, given that the majority of

Polesye territory is situated on the floodplain of the river Pripyat. Combined with drainage reclamation, it constitutes a regional environmental problem (Gusev 2022).

Currently, termination of the service period of reclamation systems (50-70 years) makes it necessary to modernize and/or eliminate them. Conducting a retrospective analysis of changes in Polesye landscapes, particularly their vulnerability to current wind erosion of soils, is necessary to determine the most natural and environmentally-friendly development policy.

Thus, the purpose of the research presented in the article is to GIS-model the 50-year dynamics of reclaimed land vulnerability to wind soil erosion using remote sensing data. An assessment of changes in the heterogeneity of the soil cover, structure, and land use types on selected pilot polygons of a large agricultural land user is given over a 50-year period. The degree of vulnerability of the soil cover and its dynamics have been established, and the optimal use of land in the future was determined on the basis of a geosystem approach to the soil cover structure.

Different models are used to figure out how vulnerable the soil cover is. These models use geoinformation systems and remote sensing data (Elyagoubi & Mezrhab 2022) and machine learning (Zhao et al. 2022). The morphometric indicators of terrain, granulometric composition, and hydrological regime of soils are interpreted as the basis for modeling soil vulnerability in most of these models (Lohani et al. 2020). Belarusian scientists also note the importance of considering the hydrological state of soils when determining adaptation measures and mitigating the consequences of droughts, particularly on agricultural lands (Meerovsky et al., 2021). Simultaneously, the assessment of soil vulnerability serves as an initial yet crucial step in the scientific validation and practical application of these measures, which should rely on the geosystem approach.

MATERIALS AND METHODS

The methodological stages of the research carried out include the soil cover vulnerability assessment before and after a reclamation regulation of the water regime taking into account the agricultural use of soils of different genesis. The study object is the territory of a large agricultural enterprise, with a high proportion of reclaimed land – the unitary enterprise "Agrocomplex Polesie", in the Pinsk district of the Republic of Belarus. The dynamics of composition and soil cover structure, and types of land on cultivated areas were spatially analyzed in the GIS environment based on the interpretation of multi-temporal (1974, 1986, 1989–1990, 2000–2003, 2018–2022) aerial photography and satellite data.

The overlay operations and calculation of summary statistics of geodata were performed using the ArcToolBox toolkit in the ArcGIS software environment – Geospatial Analyst and Geostatistical Analyst modules. Automated interpretation of multi-temporal multispectral images was performed in the ENVI software package with the selection of reliable spectral brightness channels in accordance with actual land use.

The vulnerability (predisposition) of soils to wind erosion was assessed on the basis of taking into account soil-hydrological constants in accordance with the genetic classification position of each soil variety: the limited field moisture (LFM) and capillary rupture moisture (CRM). In the Belarusian Polesye region, waterlogged conditions genetically predetermine the productivity of agricultural soils, making its use during the growing season especially important and indicative (Romanova 2015). The number of days per year or during the growing season was taken during which the moisture content in the 0–20 cm layer exceeds the LFM level and is below the CRM (significant soil-hydrological constants). It is used as the measure of assessment of the moisture supply of soil of a certain genesis and granulometric composition. Spatial consideration of the soil function of mitigating meteorological droughts due to internal predisposition makes it possible to identify the degree of risk of agricultural land degradation due to global climate change (Chervan & Melnik 2022).

The dynamics of the soil cover formation of the studied reclamation system "Parokhonskoe" of the agricultural complex "Polesye" (total area more than 9,200 ha) was studied in accordance with the geosystem approach to the soil cover structure – changes were analyzed not in individual soil taxons but in their combinations in homogeneous geomorphological, orographic and lithological conditions. This principle makes it possible to diagnose significant (irreversible) changes in soil cover in terms of probable land degradation due to economic use. We measured the amount of heterogeneity within the boundaries of soil combinations in dynamics by looking at both the coefficients of soil contrast and complexity, which is a number that shows how different and complicated the soil cover is, and the degree to which the soil is vulnerable to deflation.

The inventory of geosystems by soil combinations is based on the teachings of V.M. Friedland on the soil cover structure (Chervan et al. 2016). This approach has not found wide distribution in studies of Western Europe, USA, and Australia but has been actively developed in Belarus both for analyzing the suitability of agricultural land (Chervan et al. 2016; Chervan 2021) and assessing the biodiversity of protected areas (Romanova & Andreeva 2003; Kindeev & Mudragelova 2022). At this point, the fast growth of GIS technologies has made it possible to create adaptive landscape farming systems that are based on a multiscale analysis of the different types of soil cover. Geostatistics and pedometrics have grown in popularity recently thanks to the availability of quantitative data on the properties and indicators of the soil cover. These methods, along with a geosystem assessment, allow the soil to be shown as a discrete-continuum body (Chervan et al. 2022). Tasks for using remote sensing data are set to obtain operational information on qualitative and quantitative indicators of the state of disturbed geosystems in general and soil cover in particular (Savin 2022). The classical measures for assessing the heterogeneity of the soil cover structure developed by Yu.K. Yuodis (Yuodis 1967) are the coefficient of complexity, contrast, and heterogeneity as a complex indicator of soil cover heterogeneity used in the cadastral assessment of agricultural land and the calculation of bio- and pedodiversity (Chervan et al. 2022, Kindeev & Mudragelova 2022). The development of geoinformation systems made it possible to use the developed indicators for a comprehensive geosystemic assessment of the landscapes stability to anthropogenic impact and the development of recommendations for anti-erosion measures (Chervan et al. 2016). This allows us to determine the feasibility of utilizing these values to evaluate the changes in Polesye's soil cover due to land reclamation.

The identified soil combinations (SC) are individualized in terms of their component composition and their share in participation in the soil cover structure. Qualitative (soil genetic type) and quantitative (share of soil in combination) diversity of land use conditions are encoded through the SC formula.

The area calculation of soil contours or land plots, vector-raster transformations, and cartographic algebra were performed in the geodatabase through the ArcGIS 10.7 software package.

The degree of anthropogenic impact on the soil cover was determined by the composition of land types with an assessment of the dynamics of the land use structure simultaneously with the analysis of soil cover for the period 1974–2022. The nine arrays of representative plots with a total area of more than 2,800 hectares were selected for the purpose of increasing the reliability of the results of the geostatistical analysis. The choice of these arrays was made on the basis of different dynamics of the soil cover structure and the composition of land types over a 50-year period to confirm the hypothesis of an increase in the vulnerability of the soil cover of agricultural lands under the conditions of intensification of agrolandscapes.

Aerial photography and satellite images were used to analyze land use dynamics. Multi-temporal satellite images for each of the studied periods were used to take into account the phenology of agricultural crops and detect different phases of land use. It was combined into one composite for subsequent classification using a trainable non-parametric classifier – the support vector machine method (SVM). High-resolution remote sensing standards QuickBird and Ikonos, detailed land plans, and field survey results were used to train the classifier on the study territory.

Soil vulnerability is based on its hydrological regime, so the main thing that is monitored from afar is moisture. This is done by analyzing at radar images (Dubois et al. 1995; Meng et al. 2018; Zeyliger et al. 2020; Kang et al. 2021; Ondieki et al. 2023), as well as different normalized vegetation indices (Sadeghi et al. 2017; Colliander et al. 2017; Suk Lee et al. 2019; Wang et al. 2020; Santi et al. 2020). The temperature-vegetation dryness index (TVDI) was used to study soil moisture in addition to the traditional use of the red (red), near infrared (NIR), short-wave infrared (SWIR) wavelength ranges (Sadeghi et al. 2017; Twumasi et al. 2021) and less often the blue range (Zhang et al. 2013), reflecting the relationship between the temperature of the earth's surface and NDVI index designed to study the surface moisture of the soil and vegetation cover (Sandholt 2002). By using these indices made, we were able to learn about how soil moisture changed over 50 years and, as a result, how dangerous the soil cover was in pilot areas.

The data of multispectral and aerial photography were subjected to visual and automated interpretation to determine the structure of land use by land types and soil moisture conditions according to the NDVI and TVDI indices in accordance with the previously developed methodology (Sandholt 2002; Sadeghi et al. 2017). Remote sensing materials were selected according to the principle of similarity of shooting time during the growing season, image quality, and a single geometric and spectral (radiometric and atmospheric) correction at the post-processing stage in the ENVI 5.5 software package. Multispectral satellite images of the Landsat-5 TM, Landsat-7 ETM+, and Landsat-8 OLI/TIRS systems with a spatial resolution of 30 to 120 m for March–May 1986, 1989, 1991, 1999, 2000, 2001, 2003, 2018 and 2022 were used as a basis for the analysis in GIS. The satellite images used were selected in such a way that the shooting dates in different years did not differ by more than 2 weeks in accordance with a similar ratio of natural and cultivated vegetation. The use of these systems is due to the wide time coverage as well as the presence of a thermal infrared channel, which is necessary for calculating the TVDI index.

RESULTS AND DISCUSSION

The amount of available water that is due to the balance of rainfall, soil moisture, evaporation, and different types of water runoff is what the value of moisture reserves in soil combinations is. Belarussian approaches to genetic soil classification enable spatial differentiation based on the degree of hydromorphism, from automorphic to hydromorphic (mineral moistened and organogenic peat-bog soils). The parameterization of moisture supply was carried out in the range between LFM and CRM ranges for each element in the formulas of SC on the territory of 9 arrays of representative plots. The group most vulnerable to deflation includes soils where the range of available moisture during the growing season is below the CRM constant for more than 130 days per year (Romanova 2015). The indicators assigned to the groups of strongly-, medium-, and weakly-vulnerable soils were 101-130, 71-100, and 51-70 days, respectively. The group of the least vulnerable includes soil varieties with a moisture content below the CRM in the root layer during the growing season, less than 50 days per year.

A distinctive feature of the agricultural enterprise under consideration is the predominance of soddy waterlogged and peat-bog soils of different thicknesses and the peculiarity of the occurrence of lowland peat. It should be noted the changing dynamics of land use in agrolandscapes, from traditional farming (1960–1990) to modern intensive agricultural use in the form of saturation of crop rotations with tilled crops within the boundaries of arable and improved meadow land plots. The analyzed data for 1974 included the soil cover characteristics of agricultural lands, which were based on the first round of soil-geobotanical survey materials in Belarus. Additionally, the analysis considers the land use structure of various land types, which are identified using panchromatic aerial photography data at a scale of 1:10,000.. The results in Table 1 illustrate the relative importance of the elements of SC and land type composition in determining the susceptibility of soils to wind erosion, ranging from the least vulnerable soils (I) to the group with the highest risk of deflation (V). At the same time, the soil-hydrological constants were additionally differentiated according to the conditions for the presence of moisture resistance within the soil profile in accordance with the granulometric composition of the soil-forming and underlying rock.

Over the 50-year period, there have been significant changes in the soil cover structure caused by the intensification of agricultural use, as shown in Table 1 and Fig. 1. The spatial accuracy of the original and modeled geodata at a scale of 1:10,000 – the most detailed level for land cadastral information in Belarus – limits the measurements and calculations error. According to the first round of soil-geobotanical surveys in Belarus in the 1960s (Romanova 2015), plots 1–4 had a lot of waterlogged peat-bog and paleo-floodplain silt-gley soils. However, these plots also had soils that were breaking down because peat deposits were being actively mineralized in these agrocenoses as early as 1974. The continuing intensity of agricultural impact within arrays № 5-6, which include arable and meadow improved types of land, has led to an increase in heterogeneity of the soil cover structure over the entire period under consideration. The cultivated areas within the boundaries of arrays № 8–9 are currently characterized by less intensive inclusion in agricultural production. However, in 2022, the predominance of semi-hydromorphic (temporarily excessively moist and gleyic) soil combinations replaced the predominance of hydromorphic soils in 1974.

It should be noted all representative land plots are characterized by an increase in the heterogeneity coefficient (K_h) over a 50-year period in soil cover structure (Table 2) which simultaneously takes into account the contrast (Kc) and dissection (Kr) of elements in the soil combination formula. The areas with the most crop production and the more complex soil cover structure at the start—sample arrays № 1-4 and № 8–9 in Table 1—have a greater increase in soil heterogeneity.

The results of automated interpretation of remote sensing data for each sample array were normalized in the GIS according to the TVDI index by the method of equal intervals for 5 groups for the entire survey period. According to remote sensing data (spectral index TVDI), active reclamation and agricultural impact have increased in the proportion of soils susceptible to deflation, leading to a complex soil cover structure over a 50-year period. It should be taken into account that this spectral index is sensitive to significant meteorological changes within the vegetative season. It is planned to replace the "triangle method" used to calculate the TVDI index with the "trapezoid method" in further scientific research using data from the optical short-wave infrared wavelengths of the Sentinel-2 system due to more high spatial resolution.

The calculation of the intergroup percentage ratio allowed to determine the TVDI value for each survey date within the boundaries of each array of representative

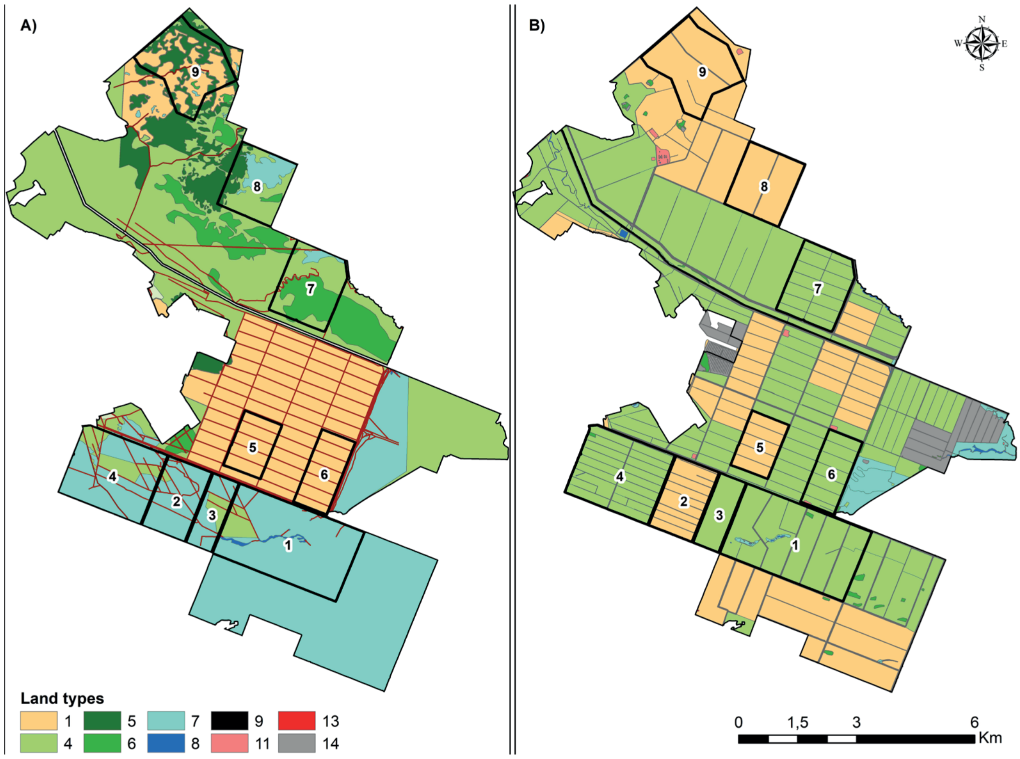

Fig. 1. Types of land of the agricultural complex «Polesye» A) 1974 year; B) 2022 year: 1 – arable; 4 – meadow improved; 5 – under shrubs; 6 – forests; 7 – swamps; 8 – water bodies; 9 – under roads; 11 – under construction; 13 – unused; 14 – other

Fig. 2. Degree of soil vulnerability A) 1974 year; B) 2022 year: 1 – the least vulnerable; 2 – weakly vulnerable; 3 – moderately vulnerable; 4 – vulnerable; 5 – the most vulnerable

plots for the period 1986–2022 (Fig. 3). Attention is drawn to the fact that most of the arrays of the agrolandscapes under consideration were characterized by a high degree of susceptibility to deflation due to reclamation and then active agricultural development. It led to the complication of soil cover structure already after 10–15 years of the reclamation system operation – they are located in the range of 3–4.5 vulnerability groups on the chart. Separate extremes (arrays № 3, 9 in May 2000; arrays № 3, 8 in May 2001) are caused by a change in the use of agrocenoses or significant meteorological differences during the plant growing season. It should be noted a significant difference in the present situation with the risk of deflation in representative areas: the greatest danger of wind erosion due to insufficient amount of productive moisture in the root layer of soils is for arrays № 2, 3, 8. It is possible that the transfer of some of them to fallow land is a forced organizational measure in connection with the loss of the productive capacity of soils on these lands. Array № 9 is also represented by fallow lands, since unfavorable phenomena in cultivated areas due to the initially more heterogeneous soil cover structure (Table 1) appeared even earlier. Arrays № 6, 7 with composed soil cover of thicker organogenic soils are currently less at risk of deflation and are used as meadow-improved lands with intensive crop rotations

CONCLUSIONS

During the review period, varying degrees of agricultural land use intensification caused significant changes in soil cover structure, which we registered through research. The heterogeneity coefficient, which is the best way to show how complex the soil cover structure is, went up by 5–10 times for most of the main soil combinations over a 50-year period. In some cases, it went up by more than 100 times (No. 6 and 7). The significant combination area from 133 to 645 indicates the significance of the studies conducted and the regional nature of changes in the soil cover structure under the influence of agricultural activity. According to the materials of ground studies and interpretation data of archival remote sensing data, it can be seen that the key area soils at the very beginning of the time period

Table 1. Dynamics of vulnerability of soil cover of representative plots taking into account of land use structure

Sample array of plots	Square, hectares	Soil combination*		Land use structure**		Vulnerability	
		1974	2022	1974	2022	1974	2022
1	645	$PB^{65}+SS_3^{25}+PBd^{10}$	$PB^{65}+SS_3^{20}+PBd^{10}+SS_2^{5}$	$Ms^{90}+S^{10}$	$M_i^{95}+O^{5}$	$II^{65}+III^{25}+IV^{10}$	$II^{35}+I^{30}+III^{25}+IV^{10}$
2	224	$PBd^{50}+PB^{45}+SS_2^{5}$	$PB^{50}+PBd^{40}+SS_2^{10}$	$S^{95}+Ms^{5}$	$FL^{95}+O^{5}$	$II^{45}+IV^{45}+V^{5}+III^{5}$	$IV^{30}+II^{30}+I^{20}+III^{15}+V^{5}$
3	133	$PBd^{55}+PB^{35}+SS_3^{10}$	$PBd^{50}+PB^{40}+SS_2^{5}+SS_3^{5}$	$S^{75}+Ms^{25}$	M_i^{100}	$IV^{50}+II^{35}+III^{10}+V^{5}$	$II^{30}+IV^{30}+V^{20}+III^{10}+I^{10}$
4	428	$PB^{70}+PBd^{20}+SS_2^{10}$	$PB^{70}+PBd^{15}+SS_3^{10}+SS_2^{5}$	$S^{80}+Ms^{20}$	$M_i^{95}+O^{5}$	$II^{75}+V^{15}+III^{5}+IV^{5}$	$I^{60}+III^{25}+II^{10}+IV^{5}$
5	150	PB^{100}	$PB^{80}+SS_3^{10}+PBd^{10}$	A^{100}	M_i^{100}	$II^{95}+IV^{5}$	$I^{60}+II^{20}+III^{10}+IV^{10}$
6	180	PB^{100}	$PB^{90}+SS_3^{10}$	A^{100}	M_i^{100}	II^{100}	$I^{75}+II1^{5}+III^{10}$
7	290	$FSS^{60}+PB^{40}$	$FSM^{60}+PB^{30}+FSS^{5}+PBd^{5}$	$Ms^{50}+US^{45}+S^{5}$	M_i^{100}	II^{100}	$I^{70}+II^{20}+III^{5}+V^{5}$
8	260	$PB^{65}+SS_3^{20}+PBd^{15}$	$PB^{55}+SS_3^{20}+PBd^{20}+SS_2^{5}$	$Ms^{65}+S^{30}+US^{5}$	FL^{100}	$II^{65}+III^{20}+V^{15}$	$I^{40}+III^{25}+II^{20}+IV^{15}$
9	341	$SS_3^{45}+SS_2^{20}+PB^{15}+SPS_2^{10}+FSS^{10}$	$PBd^{20}+PB^{20}+SS_3^{20}+SS_2^{15}+SPS_2^{15}+SPS_1^{10}$	$O^{55}+Ms^{45}$	FL^{100}	$III^{75}+II^{15}+IV^{5}+V^{5}$	$III^{50}+IV^{20}+II^{10}+I^{10}+V^{10}$

*Soils: SPS – sod-podzolic swampy (SPS1 – temporarily over-hydrated, SPS2 – gleyic), SS – soddy swampy (SS1 – temporarily over-hydrated, SS2 – gleyic, SS3 – gley), PB – peat-bog low-lying type, FSS – floodplain soddy swampy, FSM – floodplain silt-marsh, PBd – degropeat mineral residual-peaty.

**Land types: A – arable, Mi – meadow improved, Ms – meadow swampy, S – swamps, US – under shrubs, FL – fallow land, O – other (water bodies, under construction, unused lands

Table 2. Cartometric assessment of the soil cover structure of representative plots

Sample array of plots	1974			2022		
	K_k	K_c	K_h	K_k	K_c	K_h
1	9.56	0.07	0.7	10.6	0.5	5.32
2	21.53	0.09	1.89	21.9	0.48	10.6
3	18.68	0.12	2.29	20.6	0.73	15.1
4	10.49	0.05	0.53	11.5	0.43	4.94
5	2.02	0.08	0.16	6.32	0.66	4.18
6	0.13	0.04	0.01	3.3	0.51	1.68
7	0.35	0.04	0.01	3.12	0.53	1.68
8	10.83	0.05	0.55	15.6	0.46	7.22
9	7.93	0.06	0.48	12.7	0.81	10.3

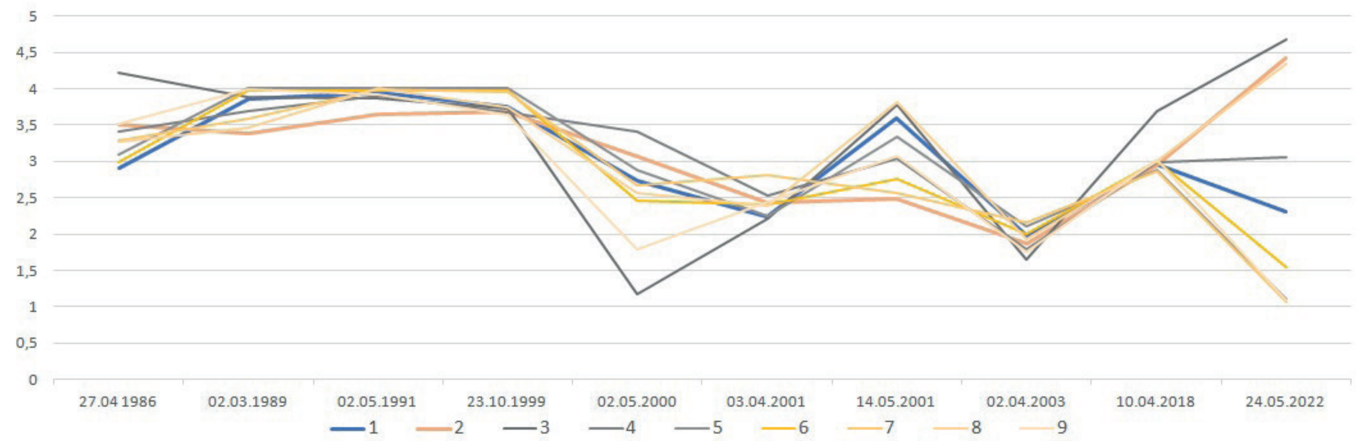

Fig. 3. Dynamics of soil vulnerability groups in sample arrays over a 40-year period

under consideration are in a state of degradation due to active peat extraction. The increasing of soil cover structure heterogeneity is observed as a result of the high intensity of agricultural production, and the proportion of automorphic soils vulnerable to deflation increases. The predominance of hydromorphic soils has been replaced by the prepotency of semi-hydromorphic soils in most of the agrolandscapes, which is noted for the entire Polesye region.

An effective measure of adaptive landscape use of the assessed lands during the review period was defined by the transformation it to a category of fallow lands, which significantly reduce the risk of wind erosion and homogenize the soil cover by increasing the role of meadow vegetation formations.

The methodology applied on the example of a key agricultural enterprise can also be applied in other physical and geographical regions of the Polesye region characterized by alluvial sedimentation in the zone of the central and terraced floodplains of the river basin. The hard-to-reach areas of the southern part of the Brest, Pripyat and Gomel Polesye are of particular interest because of "conserved" as a result of the consequences of the Chernobyl nuclear accident but also differed in the dynamics of the soil cover structure.

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