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FORECASTED TRENDS IN CHANGES OF VEGETATION IN THE EUROPEAN PART OF RUSSIA IN CONNECTION WITH GLOBAL WARMING

ABSTRACT. The paper discusses connections between zonal boundaries of vegetation and productivity of forest stands and some climatic parameters. It also suggests mathematical-cartographic models of these connections. The models are used to forecast changes in the boundaries of the vegetation sub-zones and of forest stands productivity in the European Part of Russia and on the adjacent areas for 2046–2065 under one of the scenarios of global warming.

KEY WORDS: Zoning of vegetation, growth of timber, global warming, climatic parameters, forecasts, mathematical-cartographic model.

INTRODUCTION AND BACKGROUND

The most important feature of the modern climate is global warming. It can be traced as a background process throughout the XXth century and it has become most prominent beginning in the 1970s. Climate warming is detected from meteorological observations (for a rigorous analysis, only data of the measurements of non-urbanized areas are used) and is supported by indirect evidence, of which the principal one is the rise in the oceans' level and melting of mountain glaciers. The major challenge for the modern science is the question of the climate forecast and identification of the environmental response to these changes. This paper discusses some issues related to changes in the vegetation cover (VC) occurring under the influence of current trends of climate change and a projection of its dynamics in the European Part of Russia.

It is best to consider feedbacks of VC to climatic changes under an integrated approach. This approach involves, first of all, ideas of the planetary homeostasis (i.e., the tendency of the natural system to reproduce itself, to restore the lost balance, and to overcome resistance of the external environment) that have been best reflected in the Gaia hypothesis [Lovelock, 1982]. However, with all its elegance, this concept of the biological control over the global climate must, apparently, be rejected – empirical and theoretical results show that the dynamics of the Earth's history for the global biota depended heavily on geophysical phenomena occurring on the planet [Budyko, et al., 1985].

The interaction between VC and climate can be assessed with varying level of detail. The VC properties (morphological, physical, and psychological) are considered together with soil parameters in current climate models in the calculations of various flows (heat, moisture, and carbon dioxide) between the atmosphere and the underlying surface. These are the so-called SVAT ("Soil-Vegetation-Atmosphere-Transfer") models that can be integrated or used individually. The resulting climate change calculations determine changes of the biophysical and biochemical processes in plants and soils, defining changes in species composition, length of the growing period, and the vegetation structure. The process of transition from inputs of climatic models to the VC parameters may occur at different levels of complexity. This may involve very simple regression relations and much more sophisticated models, such as EFIMOD (http://ecobas.org/www-server/rem/mdb/efimod.html; http://prezi.com/tprjzowtnuj3/2), BIOME 6000, etc. A common feature is a unidirectional approach; i.e., the information about the changes in VC is not interactively fed back to the climate model. At the same time, changes in the properties of VC influence the exchange of heat, H_2O, and CO_2 with the atmosphere, and these changes can effectively impact the thermodynamic field of the atmosphere. Thus, the so-called dynamic models of vegetation were developed. These include, for example, ORCHIDEE [Krinner, et al., 2005], JSBACH [Bathiany, et al., 2010], etc., that are interactively connected with the atmosphere component of climatic models. Such systems are already able to reflect feedback-based transient changes.

This paper treats changes in VC through static relations, i.e., regression equations. The use of the simplest approach is quite reasonable since the use of complex models does not often produce reasonable results due to requirements for very precise information of the VC parameters. VC is characterized through its zonal boundaries and productivity parameters of woody plants.

Shifts in zonal boundaries of vegetation are found in different regions of the world. With sufficient moisture, they are most likely where the temperature is the limiting factor [Turmanina, 1976]. Therefore, the most noticeable changes can be observed at the northern limit of the distribution of woody vegetation: with global warming, the forest boundary at high latitudes is expected to shift north [Turmanina, 1976; Velichko, 1992; Malkhazova, et al., 2011]. Modern research in the polar regions of Siberia has identified the spread of woody vegetation to the north. Thus, for the world's northernmost forests in Khatanga (Taimyr) over the last 30 years, a 65% increase of larch canopy closure and their shift into the tundra area at 3–20 m/yr have been detected [Kharuk, et al., 2006]. Unfortunately, similar data are not available for the southern regions of Russia.

Establishing the quantitative relationship between the zonal boundaries of VC and climatic parameters is associated frequently with an array of problems that relate to complex relations between VC and climate change, to uncertainty in dependencies between VC boundaries and climate, to vegetation system inertia, to multi-factorial nature of climatic impacts, and to uncertainty of the definition of the notion of "zonal boundaries" itself [Malkhazova, et al., 2011].

Quantitative analysis of the effect of climate on the *productivity of forest stands* is of particular importance for the assessment of resource-biosphere relationships. *Growth of timber* is an integral indicator of stand productivity. Growth of timber is defined by biological characteristics of the species and by the entire array of abiotic factors, among which, climate is of paramount importance. Warming, in conditions of the shortage of heat supply, leads, apparently, to an increase in productivity of forest stands in Russia and some European countries (0.5% per year from 1961 to 1998) [Alekseev and Markov, 2003].

The goals of this work included identification of climate indicators that are most associated with vegetation, establishment of forms of these relationships, and assessment of forecasted values of selected vegetation characteristics based on climatic models for the mid XXIth century [Kislov, et al., 2008; Kislov, 2011]. As a result, mathematical and cartographic models of relationships between vegetation zoning and productivity for the European Part of Russia (EPR) and some climatic parameters were built. These models were used to forecast possible changes in the boundaries of the vegetation sub-zones and in stand productivity in the EPR in the middle of the XXIth century caused by global warming.

MATERIALS AND METHODS

Climatic data. Information about the spatial distribution of climatic parameters used in the above-mentioned models characterizes the EPR and the adjacent areas. The territory is broken into a grid with a 2 S 2 deg. cell size.

The data for the period from 1961 to 1989 inclusively (that are called a «period of the modern climate» on the recommendation of the World Meteorological Organization) are the results of the NCAP/NCEP re-analysis [Kislov, 2011; Kislov, et al., 2011] interpolated to the nodes (the geometric centers of the cells) of the degree grid. For each node, a range of climate parameters was calculated. It was assumed, that their values for the node (point) can be extrapolated to the whole cell (polygon).

Structurally similar projections for 2046–2065 are based on the data of numerical experiments carried out with climatic models under the project CMIP3 (*Coupled Model Intercomparison Project*) of the WCRP (*World Climate Research Program*). For the characteristics of the future anthropogenic impacts, "A2" scenario (i.e., one of the most "harsh" scenarios of the IPCC (*Intergovernmental Panel on Climate Change*)) was adopted [Kislov, 2011; Kislov, et al., 2011].

Of a variety of available climatic parameter, the parameters selected for the analysis are as follows:

1) Effective air temperature ($T > 10°C$). The analysis considered a number of days with effective temperature and the annual sum of such temperatures. These indicators are considered the major climatic characteristics of plants growing season.

2) The hydrothermal coefficient (*HTC*) by Selyaninov:

$$HTC = Sum\_R / 0.1 \cdot Sum\_T \qquad (1)$$

where: Sum_R is the total precipitation for the year; Sum_T is the sum of effective temperatures for the year.

Zoning of vegetation. Possible changes in the vegetation zones boundaries were assessed based on the map "Zones and types of vegetation belts of Russia and adjacent territories" [Zones and types..., 1992]. This map represents the most common understanding of the modern zoning of vegetation, while satisfying the fullest the requirements to scale and detail. It was assumed that the map represents the equilibrium of the zonal boundaries of vegetation and of the conditions for the "period of the modern climate".

Within the EPR, the following categories of the classification of flatland vegetation are used (zones and sub-zones, in accordance with the legend of the map (Fig. 1A)

A. Tundra zone. *Sub-zones*: A2 – arctic tundra (*only on some islands of the EPR, however, is considered in the numbering system*); A3 – northern hypoarctic (typical) tundra; A4 – southern hypoarctic (shrub) tundra.

B. Taiga zone. *Sub-zones:* B1 – forest tundra; B2 – northern taiga; B3 – middle taiga; B4 – southern taiga; B5 – sub-taiga (mixed forest).

C. Deciduous forest zone. *Sub-zones:* C1 – broadleaved forest; C2 – forest-steppe.

D. Steppe zone. *Sub-zones:* D1 – northern (bunch-grass-turf) steppe; D2 – middle (dry) steppe; D3 – southern (desert) steppe.

E. Desert zone. Sub-zones: E1 – northern desert; E2 – middle desert; E3 – southern desert (*not present in the study area under modern conditions, however, is present in the forecast – see below*).

The analysis was performed at the level of the vegetation *sub-zones*. Within the study area, they were numbered from north to south from "1" (A2) to "16" (E3).

Fig. 1A shows the distribution of the nodes and degree grid cells over the map of the modern zoning vegetation [Zones and types..., 1992]. The analysis was performed separately for the nodes and cells, as their spatial association with the vegetation sub-zones boundaries differed somewhat. Excluded from the analysis were the nodes and cells that were outside the boundaries of the vegetation units identified on the map, as well as the islands (except for the largest), mountain areas, and seas. Each node or cell was assigned a number of the sub-zone. It was assumed:

- for the nodes – the node is within the sub-zone;
- for the cells – more than 50% of the area of the cell is within the sub-zone, even if its geometric center (node) is located outside the sub-zone.

The analysis of the map (Fig. 1A) showed that a significant number of the nodes (at least 20%) are almost on the boundaries of the sub-zones. Approximately the same number of the cells is divided by these boundaries practically in half. If we consider that the accuracy of the zonal boundaries on the map is, to some extent, relative, it can be concluded that the assignment of specific nodes or cells to a particular sub-zone, in some cases, is rather arbitrarily, particularly in the northern areas where the latitudinal extent of the sub-zones is minimal. However, all the nodes and cells, with some assumptions, have been confined to specific sub-zones (Fig. 1B).

Growth of timber. The analysis was based on the data on stocks and growth of forests from the statistical materials of the State Accounting of the Forest Fund (SAFF) for 1963–1990. Of a large number of forest

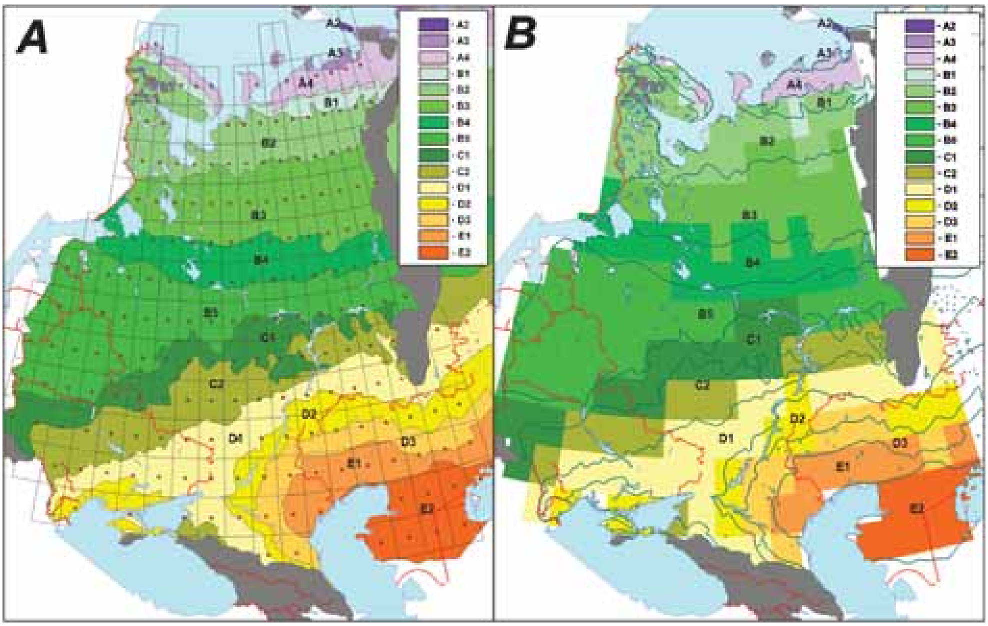

Fig. 1. A – the cells (polygons) and the nodes (points) of the degree grid used as the locations of the climatic data when superimposed with the map of the current zoning of vegetation.
B – sub-zonal locations of the grid cells.
A2-E2 – vegetation sub-zones (see text). Gray color indicates mountain areas

taxation parameters in the data of SAFF for all groups of tree species, the following parameters were selected for the analysis:

The total stock of timber is the amount of raw stem wood of all the trees of the forest stand. It depends on many factors, including, the forested area, the average age of the stand, etc.

The total average annual growth of timber is the parameter that characterizes the annual increase of the stem stock of the forest on average for the entire period of its life. This is an integral stand productivity index that reflects conditions of its development, including climatic.

To analyze the relationships between climate and productivity parameters, 36 administrative regions of the Russian Federation within the EPR were selected. Most of them are located entirely within the forest area, but there are others where the forested land occupies a relatively small area (Belgorod, Orel, Kursk Oblast, etc.). Therefore, the analysis was carried out for all the regions and separately for those fully located within the forest areas.

The data of SAFF were recalculated to arrive at the units of "m^3/ha of forested area." Thus, the parameters for the "average stock" and "average growth" of trees were obtained; then they were used to calculate the average long-term values for 1961–1988 for each of the selected Russian administrative regions.

The map of the administrative regions was superimposed with the degree grid (see above). The multi-year weighted average (for the area) climatic parameters were calculated for each administrative region of the Russian Federation; the calculations were made considering the set of the grid cells that cover each region and the proportion of the cells' area for the region.

Then, the relationships were assessed (Pearson correlation coefficients of the pairs) between:

– the values of climatic parameters and the sub-zonal locations of the nodes and cells (numbers of sub-zones); the results are shown in Table 1;

– the values of climatic and productivity parameters; the results are shown in Table 2.

The linear regression equations calculated for these indicators were then used to support and build the forecast models.

Data processing and calculations were carried out with *MS Visual FoxPro* and *STATISTIKA* software. Cartographic work was carried out in the *MapInfo Professional* GIS environment.

RESULTS AND DISCUSSION

Zoning of vegetation

Table 1 shows that the level of relationships between the climatic parameters and numbers of the sub-zones is very high. It is somewhat lower for HTC, but is especially high for effective temperature: 0.97 both for the cells and the nodes. This provided the basis for the calculation of the regression

Table 1. Correlation coefficients of the climatic parameters and the numbers of vegetation sub-zones*

Parameter	Sub-zonal locations (sub-zones numbers) of the nodes and the cells of the grid	
	nodes	cells
HTC by Selyaninov	–0.81	–0.79
Number of days with T0C > 100	0.92	0.92
SumT0C > 100	0.97	0.97

*All correlation coefficients are significant at $p < 0.01$.

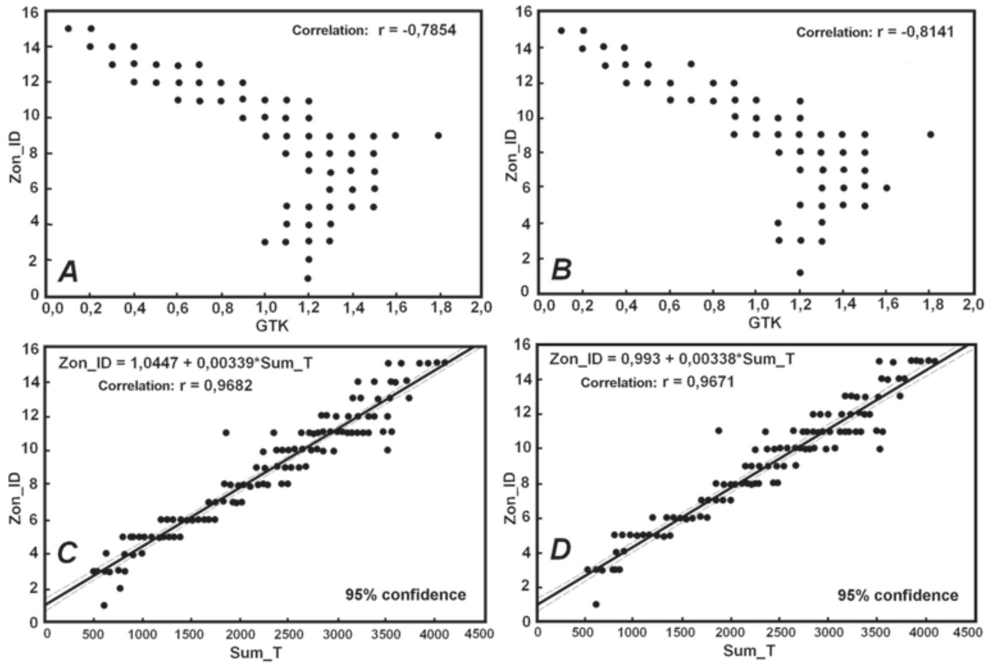

Fig. 2. The relationships between the order numbers of the vegetation sub-zones (Zon_ID), HTC by Selyaninov (HTC), and the sum of effective temperatures (Sum_T).

***A, B** – HTC (**A** – for the cells, **B** – for the nodes), **C, D** – the sum of effective temperatures (**C** – for the cells, **D** – for sthe nodes)*

relationships between the sub-zonal locations of the grid's nodes and cells and the climatic parameters (Fig. 2).

Fig. 2 shows nonlinear relationships for the HTC parameter; however, these relationships were not analyzed at the current stage; therefore, HTC was not used in the forecast.

We can also see that the sum of effective temperatures actually shows a linear relationship with the vegetation zoning. A similar pattern was obtained for the number of days with effective temperature, although in this case, the strength of the relationship was somewhat lower (Table 1), so the graphs for the last case are not given.

Thus, the sum of effective temperatures appeared to be the best parameter of all climatic parameters considered for the forecast of possible changes of the vegetation sub-zone boundaries in the EPR in the middle of the XXIth century; this parameter had the tightest connection with the vegetation zoning (Fig. 2, Table 1).

The relationships betweens the sub-zonal locations of the nodes and cells of the grid and the values of the sum of effective temperatures parameter are described by two regression equations (Fig. 2). Modification of some of these formulas (averaging the values of the coefficients for the nodes and cells) allowed arriving at the following equation applicable both to the cells and the nodes.

$$Zon\_ID = 1 + 0.0034 \cdot Sum\_T, \quad (2)$$

where: *Zon_ID* is the serial number of the sub-zone (1–15),

Sum_T is the sum of effective temperatures.

Using the existing forecast values *Sum_T* in equation (2) made it possible to determine the potential location of each cell of the degree grid for 2046–2065 in the zoning system, defined by the sum of effective

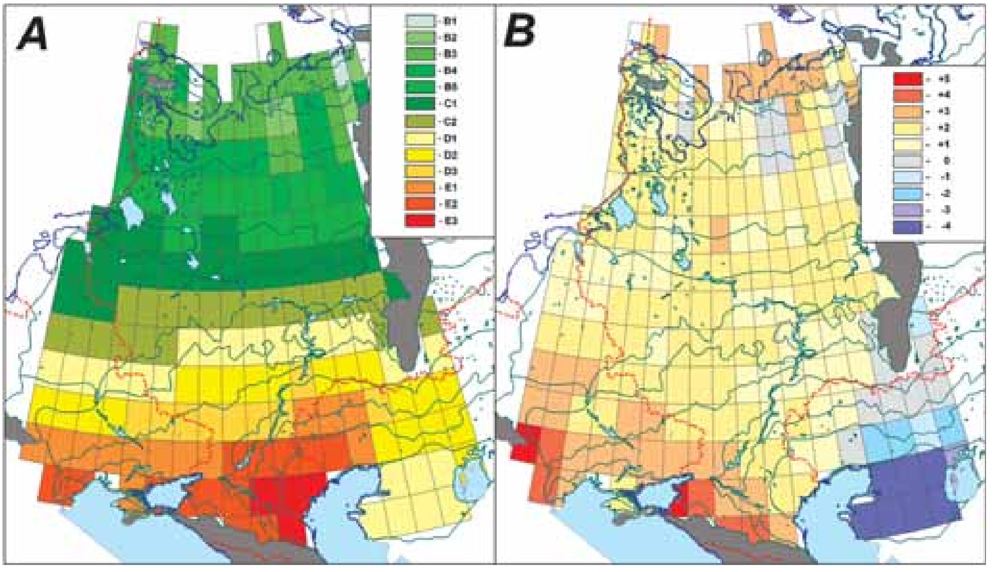

Fig. 3. A – 2046–2065 potential sub-zonal locations of the grid cells defined by the sum of effective temperatures. B – projected "shifts" – potential changes of the sub-zonal locations of the degree grid cells for 2046–2065 determined by the sum of effective temperatures.

*B1–E3 – parameters of the vegetation sub-zones (see text and Fig. 1), corresponding to the grid cells according to the forecasted temperature conditions for 2046–2065. The values of a "shift" (change in the number of the sub-zones): (+) – shift of the sub-zonal boundaries to the north (warming), (–) – shift of the sub-zonal boundaries to the south (cooling), (0) – no "shift." For **A** and **B**: "empty" cells indicate that the forecasted results are not reliable; green lines – the modern boundaries of vegetation sub-zones (see Fig. 1)*

temperatures. The same can be applied to the nodes, but in this case, the cartographic representation of the results is less evident.

Obviously, the time interval between the "period of the modern climate" (1961–1989) and the forecast period (2046–2065) is not sufficient to predict the real change of zoning boundaries, that, if at all possible, may manifest itself only locally. One can only talk about the potential conditions that determine the character of vegetation in the middle of the XXIth century. In any case, the inertia of vegetation as a system would not allow it to reach the state of equilibrium with changing climatic conditions by the middle of the XXIth century.

Considering this discussion and using equation 2, the potential locations of specific cells of the grid in the vegetation sub-zones system that correspond to the forecasted 2046–2065 changes in the thermal conditions were calculated and presented in a map format (Fig. 3A).

For greater clarity, we calculated "shifts" of corresponding values of the sub-zonal locations of the grid cells. The "shift" means the difference between the forecasted and the modern values of the sub-zone numbers (1–16) of the current cell. The "shift" can be positive (the forecasted value is greater than the modern – "warming"), negative (the forecasted value is less than the modern – "cooling"), or "zero" (no change forecasted) (Fig. 3B).

The map in Fig. 3A (in comparison with Fig. 1) shows the tendency of the northern shift of the sub-zonal boundaries in the future for almost the entire territory under the discussion. The exception is the individual cells in the northern EPR, for which the results of the forecast are considered less reliable.

Fig. 3B (in comparison with Fig. 1, 3A) shows that for tundra and forest-tundra of the EPR, the forecasted trends in the "shifts" of the sub-zonal boundaries correspond to the established ideas. The development of favorable, for forest vegetation, conditions is expected. In this case, in the north of the territory for individual cells, there are very significant "shifts" leading to a situation where, for example, on the Kola Peninsula, the forecasted temperature conditions in some places will support the growth of southern taiga or mixed forests (Fig. 3A).

Negative "shifts" within the study area are forecasted primarily outside of Russia, for the northwest of Kazakhstan; within Russia – for the southern Urals (Fig. 3B).

Growth of timber

The results of the calculations of the Pearson correlation coefficients of pair values presented above (Table 2) show that the most significant connection between vegetation productivity and climate exists only for the pair "the total average annual growth of timber – the sum of effective temperatures". In this case, the connection becomes stronger if only the forest regions are included (Table 2, Fig. 4). Accordingly, these parameters were used to predict trends in vegetation productivity for the period 2046–2065 in the EPR.

The relationship between the total average annual growth of timber (*GT*) and the sum of effective temperatures established in the calculations can be expressed by the following equation of the linear regression with the correlation coefficient equal to 0.92 (see Table 2):

$$GT = -2{,}007 + 0{,}0026\ S\ Sum\_T, \qquad (3)$$

where: *GT* is the average growth of timber (m^3/ha); *Sum_T* is the sum of active temperatures.

Table 2. Correlation coefficients of climatic and productivity parameters for the selected regions of the EPR

Pairs of parameters	All regions (*n* = 36)	Forest (*n* = 23)*
Average stock of timber –> HTC	0.10	0.17
Average stock of timber –> Sum of *T* > 10°C	**0.39**	**0.65**
Average growth of timber –> HTC	–0.29	–0.16
Average growth of timber –> Sum of *T* > 10°C	**0.80**	**0.92**

*Forest steppe and steppe regions are excluded.
In Italics – correlation is insignificant. In Bold – correlation is significant at $p < 0.05$. Normal font – correlation is significant at $p < 0.5$.

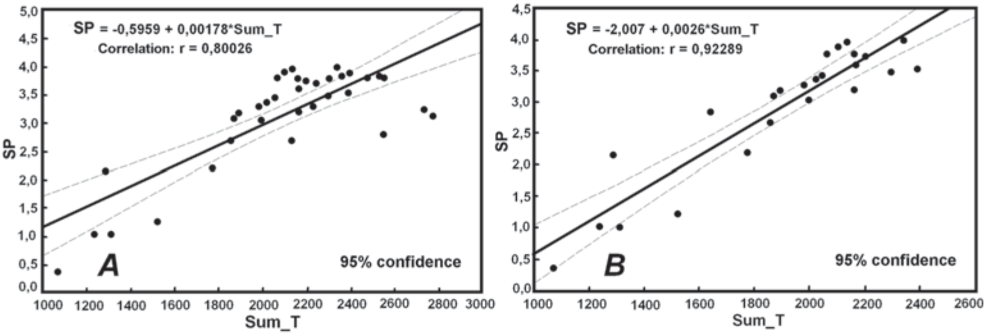

Fig. 4. The relationships of the average growth of timber (GT) and the sum of effective temperatures (Sum_T) for the regions of the EPR.

A – all regions, B – only the "forest" regions

Table 3. The forecasted for 2046-2065 changes in the timber annual growth for the "forest" regions of the EPR

Administrative regions of the Russian Federation	Average annual growth of timber (m3/ha)		"Shift"*
	1961–1990	2045–2065	
Arkhangelsk Oblast	1.03	2.51	1.48
Bryanks Oblast	4	5.54	1.54
Vladimir Oblast	3.7	4.98	1.21
Vologda Oblast	2.2	3.72	1.52
Ivanovo Oblast	3.8	4.68	0.88
Kaluga Oblast	3.97	5.12	1.15
Kirov Oblast	2.7	4.07	1.37
Kostroma Oblast	3.11	4.14	1.03
Leningrad Oblast	2.85	3.81	0.96
Moscow Oblast	3.73	4.96	1.23
Murmansk Oblast	0.38	1.91	1.53
Nizhnyi Novgorod Oblast	3.6	4.82	1.22
Novgorod Oblast	3.2	4.17	0.97
Perm Oblast	2.16	3.82	1.66
Pskov Oblast	3.05	4.43	1.38
Smolensk Oblast	3.9	4.78	0.88
Tver Oblast	3.3	4.4	1.1
Yaroslavl Oblast	3.43	4.46	1.03
Republic of Karelia	1.25	2.55	1.3
Republic of Komi	1.04	2.42	1.38
Republic of Mari El	3.2	4.82	1.62
Republic of Udmurt	3.38	4.54	1.16
Republic of Chuvash	3.49	5.14	1.65

* "Shift" means the change between the forecasted and the current values of the growth of timber parameter, m^3/ha .

Using forecasted values of *Sum_T* for the EPR for 2045–2065 in equation (3), we can calculate the potential value of the average annual growth of timber for each analyzed point in the territory. Additionally, we calculated the "shifts" in the values of the average annual growth of timber defined both for the forecasted and the modern periods (Table 3, Fig. 5).

The results show a general trend in the productivity growth of the stands, resulting in higher values of the forecasted average growth of timber for 2046–2065 compared with the current climate. Particularly significant increase in the growth and thus its maximum values are forecasted for the southern and eastern parts of the territory. Thus, the greatest "shifts" in the productivity are expected for the Middle Volga region (Republic of Mari El – 1.62 m^3/ha, Republic of Chuvash – 1.65 m^3/ha) and the Middle Urals (Perm Oblast – 1.66 m^3/ha).

It should be noted that this forecast is possible only in conditions of sufficient moisture supply in these areas, that is, if an increase in annual precipitation occurs. The

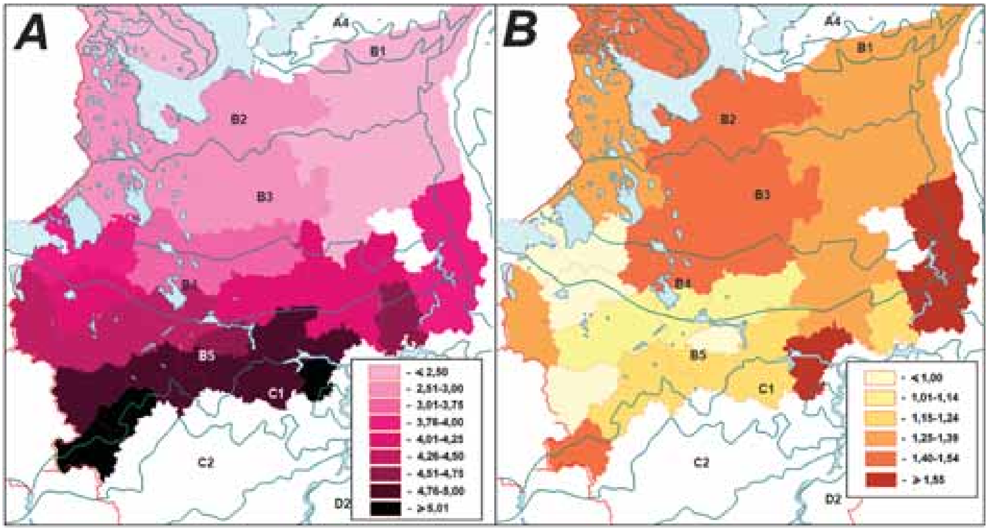

Fig. 5. A – 2046–2065 forecasted average growth of timber (m^3/ha). B – Forecasted "shifts" of the average values of growth of timber in comparison with the period of "the modern climate" (only for "forest" regions of the EPR). Explanations are in the text.

There are no data for the Komi-Permyak AO (the "white spot" on the map). Vegetation zones and sub-zones (boundaries and parameters) – see above

noticeable "shifts" are also projected for the most northern regions – the Murmansk and Arkhangelsk regions. If, at the present time, the average increase is small and is 0.38, and 1.03 m^3/ha, respectively, in 2046–2065, the growth is forecasted to increase by 1.5 m^3/ha, i.e., 2.5–3 times (Table 3). This is consistent with the established current ideas that the most significant changes in forest vegetation will occur at the northern limit of its distribution, where the conditions for the existence of forest are extreme, and that specifically temperature is a limiting factor in the development of trees and in their productivity.

CONCLUSION

The results of the analysis show that the forecasted "shifts" of the sub-zonal boundaries of vegetation associated with the thermal conditions of the growing season can have both positive ("warming" – "shift" in the conditions determining the northern shift of the existing sub-zonal boundaries: almost the entire EPR) and zero (there is no "shift": the individual cells in the EPR) trends. In some regions of the south part of the study area, the "shifts," according to the forecasted changes in the temperature conditions, can have even a negative trend.

For the growth of timber parameter for the entire territory under the discussion, only positive "shifts" are forecasted. However, it should be kept in mind that this parameter is not tightly connected with the climatic conditions. It is known, that growth of timber for each forest species increases along with better climatic conditions only to some point after which the growth slows down [Romanovsky and Schekalev, 2009].

The results obtained demonstrate the relationships between the vegetation parameters and the sum of effective temperatures only. It can be assumed that the results are reliable only if current, for the area, conditions of sufficient moisture supply are preserved. The analysis performed earlier [Kislov, et al., 2008; Kislov, 2011] shows that in the EPR (except for its southern border), warming occurring simultaneously with the growth of precipitation maintains moisture supply that is close to the modern conditions. This confirms the representativeness of the results.

It must be stressed that the forecast considers, especially with respect to the zonal boundaries, trends of changes and not the changes themselves. It is possible that the real "shifts" of these boundaries in the EPR by the middle of the XXIth century will be manifested only locally because of insufficient succession rates. This, however, does not mean that the impacts of climate change on the discussed territory are small. In fact, it means that most of the plant communities in the area will exist in temperature conditions not characteristic to the area, for indefinitely long period. In the short term, it is highly desirable to attempt to assess the possible consequences of such non-equilibrium state of the ecosystems. ■

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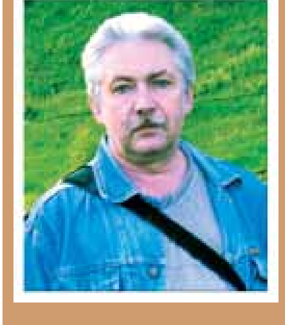

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