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Satellite-Derived Spatiotemporal Variations of Forest Cover in Southern Forest–Steppe, Central Russian Upland

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Abstract—Forest cover dynamics derived from detailed archival and recent satellite images was studied in the southern forest–steppe within Belgorodskaya Oblast, Central Russian Upland. We analyzed data from 5 sites of the total area of 1722 km^2, representative for diverse environment of the region. The forest cover increased by 31% during 1970–2014. Fragmentation of lands with forest cover was noted. Number of separate woodlands has increased by 87% and the mean size of woodland has decreased from 13.0 to 9.2 ha. Mean linear movement of the forest margin towards steppe tended to decrease from northwest to southeast. The largest advance of 34.3 m of the forest margin was found in the humid western part of the region, while it was as small as 15.0 m in dry southeast. Mean distance of forest advancement since 1970 was 24 m, as measured at 1285 study sites. The distances of forest expansion significantly differed between forest–steppe and steppe domains of Belgorodskaya Oblast. The expansion cannot be attributed to northern or southern exposition of the forested slopes of river valleys and ravines.

Keywords: percent forest cover, forest dynamics, Central Russian Upland, forest–steppe, satellite images

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Assessment of the processes of reforestation and changes in forest cover is necessary for obtaining a realistic view on trends in vegetation cover development. Solutions of this problem for the territories whose landscapes have been significantly transformed as a result of economic activity is of particular relevance. An example of such region is the south of Central Russian Upland, where the main area is occupied by agricultural lands, with wooded lands in the past covering large areas (Chendev, 2008; Arkhipova, 2014). There were significant changes, mainly as a result of logging. One of the consequences was high fragmentation of forests (Mikhno, 2012; Ukrainskii et al., 2017). Reforestation there is necessary for the improvement of soil and agroclimatic resources reproduction, as well as for generally optimizing the region's ecological conditions (Postolov et al., 2005; Kuzmenko et al., 2013).

Analysis of long-term climatic data showed that the territory of Central Chernozem Region from the early 1980s until 2010 displayed an increase in mean annual temperature by 1.0–1.3°C; annual precipitation increased and winter period shortened by 10–12 days. These factors contributed to an increase in the duration of the period of biological activity (Lebedeva, 2008; Novikova et al., 2017). Dynamics of climatic factors should naturally affect vegetation cover and its development, including trends in the dynamics and rates of change in the forest cover. These suggestions determine the relevance of this study.

Multi-temporal satellite imagery is one of the most effective sources of information for a number of forest monitoring tasks (Borrelli, 2014; Schmidt et al., 2015; Zhirin et al., 2016), which includes assessment of spatial and temporal changes of forested lands (Potapov et al., 2008; Shchepashchenko et al., 2015; Potapov et al, 2015). The combined use of archival and modern high spatial resolution images makes it possible to numerically assess the dynamics of forest vegetation ranges over many decades.

This study aims to assess the spatial and temporal changes of forest cover in the South Russian Upland (analysis of the outlines of forest range areas, as well as the change in the position of their boundaries) by the use of archival materials and modern high resolution satellite imagery from the period of 1970–2014. In the framework of this goal, the following main tasks were necessary to solve: identification of trends in the changes of forest cover in the region and its quantitative assessment; and analysis of distances at which there was movement of the forest boundaries, including slopes of different exposures, as well as in the forest–steppe and steppe zones.

The study was based on the analysis of high spatial resolution multi-temporal satellite images, which made it possible to achieve significant representative-

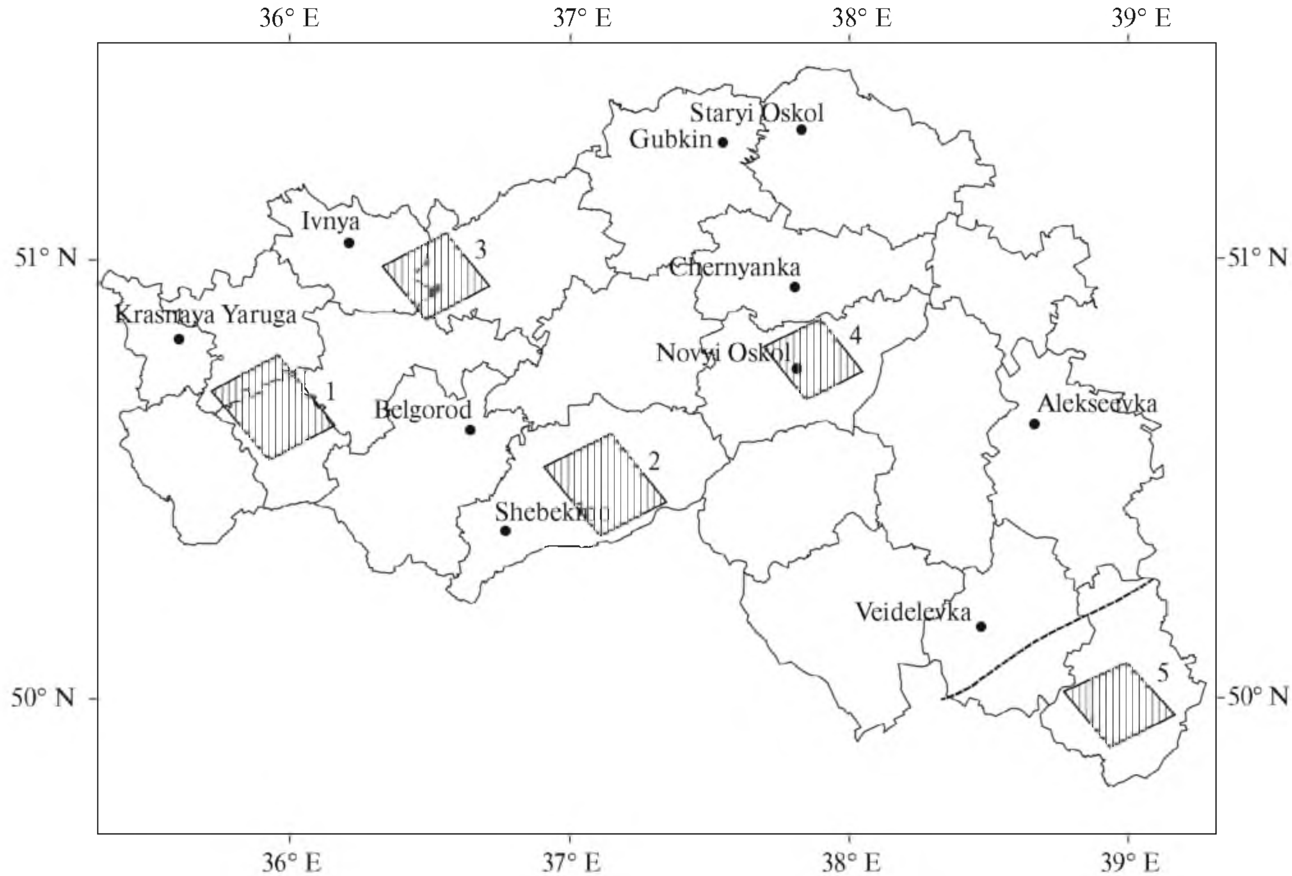

Fig. 1. Location of study areas, 1–5, on the territory of Belgorodskaya oblast. Dotted line designates the border between forest–steppe and steppe zones.

ness of the original data, as well as their wide spatial coverage. Multi-temporal remote sensing materials were the only reliable high quality sources that provided for the planned study.

MATERIALS AND METHODS

An experimental study was conducted in Belgorodskaya oblast. Most of the region corresponds to the forest–steppe zone, and the extreme southeast to the steppe zone. Hydrothermal coefficient varies from 1.25 in the northwest to 0.97 in the southeast.

Forests in the region are represented mainly by interfluves near river sistems oak and aspen forests in ravines. An important peculiarity of the forested lands is its wide distribution of small woodland areas (Terekhin, 2016).

Assessment of the directionality and speed of forest formation required highly detailed satellite images for the realistic assessment of spatial and temporal changes in the boundaries of forests and quantitative study of this process. For this purpose, we selected 5 key sites in the region with a total area of 1722 km^2 (Fig. 1), for each of which were matched pairs of multi–temporal satellite images with a spatial resolution of 2 m/pixel. Key areas of the study were chosen in such a way as to represent a set of physical, geographical and forest conditions in the south of Central Russian Upland; in particular, hydrothermal and geomorphological features of the studied region were taken into consideration. The sites were placed after considering the analysis of temperature and precipitation distribution maps, while respecting the identity of geomorphological conditions in the density of detected erosion forms of the valley–ravine network using the Atlas (*Prirodnye*..., 2005). Area 1 was 420.7 km^2, area 2—415.1 km^2, area 3—304.0 km^2, area 4—261.2 km^2 and area 5—321.2 km^2.

Satellite images analyzed at the initial date were CORONA–system generated (https://lta.cr.usgs.gov/declass_1) in the summer of 1970; data were obtained from a resource of the National Geological Survey EarthExplorer (http://earthexplorer.usgs.gov/). Satellite data of the machine series are the most detailed satellite images from the 1960s–1970s and provide an unique opportunity for retrospective evaluation of changes of environmental components, including forests.

Satellite imagery of the modern period was obtained from the ArcGIS online World Imagery (https://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer). They included mosaic images with resolution 2 m/pixel, obtained during the summer period of 2014. Thus, the time interval of the study between two dates filming was 45 years.

For realistic analysis of the territorial changes that occurred within the boundaries of forests during the estimated period, geographical reference and geometric correction were conducted for all satellite data used. These types of work were performed in ERDAS IMAGINE and ArcGIS software. Corresponding procedures allowed us to accurately combine different–time images with each other, which was a key condition for the analysis of changes in the boundaries of forest areas.

Within each key area in the ArcGIS geographic information environment, we then conducted detailed and continuous mapping of the wooded lands on the analyzed dates. It was performed by manually digitizing the contours of the areas of woody vegetation from geographically linked satellite images. Similarly, interpretation of forests was carried out at each analyzed area and allowed us to consider several thousand forest areas. When analyzing the satellite data used, it was possible to observe even the smallest changes, including the appearance or disappearance of small groups of trees with an area of several hundred square meters and, more importantly, to accurately identify changes in the boundaries of forest areas. As a result, vector layers characterizing territorial features of forested lands in 1970 and 2014 were prepared. Detailed census of even small forest areas (100–1000 m^2) was important for a reliable assessment of changes in forest cover in the region due to the high mosaic and fragmentation of forest plantations (Terekhin, 2016). Small forests make a significant contribution to the total area of forested land. However, their census would be problematic in the study of forest cover from less detailed satellite materials.

Based on the data obtained, an analytical sample was formed, which allowed us to analyze numerical changes in the area and parameters of forested lands that occurred during the period under study. Statistical analysis of the data was performed in the STATISTICA software, which included assessment of changes in total forest area, mean forest massifs and their amount.

The main experimental stage was assessment of forest massif boundaries. Results of GIS mapping of forested lands allowed us to perform spatial and temporal assessment of changes in forested lands at each key area and selecting polygons for the analysis of transformations of forest area boundaries. In this study, the estimation of linear rates of forest boundary change on the slopes of river valleys and ravine systems of northern and southern exposures. Estimation of the rates, m/10 years, was conducted based on the analysis of a sample from measurements of the distances at which forest boundary was moved during the analyzed period.

The comparison of linear rates of the advance of forest area boundary movements on the slopes of northern and southern exposures were conducted based on the assumption that forest conditions on the slopes of contrast (polar) exposures with different parameters of illumination and moistening might have influenced the intensity of the forest appearance and, in particular, the rate of linear extension of forest boundaries. Measurements were conducted on a set of test forest areas selected due to the following criteria:

(1) Forest areas are selected in such a way that the slope on which they are located should not be limited to car roads or railways, settlements, agricultural land, and especially arable land. The fulfillment of this condition was complicated by the fact that Belgorodskaya Oblast forests are often located among agricultural land or recreational areas. Nevertheless, it was possible to select a representative sample of forest areas where relevant measurements were done. In assessing sample representativeness, it was assumed that measurements should cover a group of slopes facing north and south, and that total number of measurements should be at least several hundred.

(2) Slope exposure should be determined based on joint analysis of geographically referenced images and digital terrain models, which we used from freely available SRTM data (spatial resolution 30 m). The images, thanks to their high detail and accuracy, allowed us to reliably determine slope exposures and SRTM data involved in the analysis, as it allowed geographical assessment of the distribution of slopes on northern and southern exposures.

Experimentally, the sample was formed as the result of measurement in the geographic information system of the distances between the borders of woodlands in 1970 and 2014, Estimation of distances, to which movement of forested land boundaries occurred in the period from 1970 to 2014, includes analysis of their linear increments on the slopes of the polar exposures and comparison of the mean value of increments of the forest habitat boundaries in the areas under study. The obtained data, in turn, allowed us to estimate the mean rate of change in the position of forest boundaries in 5 studied areas.

The next stage of the study was statistical analysis of the data. It included determination of the mean distance by which the forest boundary was shifted and the assessment of standard deviation. Thereafter, the rate of linear change for the position of forest boundaries was calculated; it was compared on the slopes of contrast exposures; analysis of the changes for the territory of forest–steppe and steppe zones was conducted.

At the final stage, obtained results were analyzed in conjunction with trends in the dynamics of climatic parameters observed in the southern part of the for-

Table 1. Characteristics of the forested lands changes estimated on key areas in 1970–2014

Area	Square of forests, ha		Mean square of forest massif, ha		Forest cover, % of total square	
	1970	2014	1970	2014	1970	2014
1	9103.1	12099.9	13.5	8.4	21	29
2	8943.2	10824.3	18.2	14.7	22	26
3	2855.3	4594.8	12.5	8.8	9	15
4	5829.1	7171.8	14.7	11.4	22	27
5	939.6	1907.1	2.8	2.9	3	6
Totally	27670.2	36598.0	13.0	9.2	16	21

est–steppe of Central Russian Upland during the study period. According to the results of observations at weather stations located within the south of the Central Russian Upland (Belgorod, Bogoroditskoye–Fenino and Valuiki), the results were compared with changes in air temperature and rainfall. Results were also compared with changes in the duration of the winter period.

RESULTS AND DISCUSSION

The assessment of spatiotemporal changes in forested land showed that each key study area has a clear trend of increasing forested square over time. Territorially, it is manifested in expansion of forest boundaries, overgrowth of the ravine network, and emergence of new forest areas, mainly due to small groups of trees (Fig. 2). The process of forest area expansion was observed in those areas where it was not hindered by agricultural lands, road network, and settlements adjacent in many places to the forests. Such areas were flat and sloping surfaces of ravines and in some cases slopes of river valleys covered with meadow–steppe vegetation (hayfields and pastures).

Detailed mapping of forested lands on different time sections allowed us to obtain quantitative data on the dynamics of forest cover based on a sample of several thousand forest massifs.

Based on the data obtained for 5 key areas, we found that the study area forest cover increased in the period of 1970–2014 by 31% from the level of 1970 (Table 1), which is a significant value. The greatest modern forest cover (29%) was noted on the extreme western section, the smallest (6%) is typical for the southeastern (steppe) section. Table 1 shows that the value of forest cover at the initial and final analyzed dates, in the southeast of the region (north of the steppe zone) is significantly different from the forest cover on other test areas (forest–steppe zone). At the same time, the trend of forest cover increment is clearly seen in each of them. Based on the fact that the increment of forest cover was observed in all analyzed areas located in different parts of the study area, positive dynamics of forest cover should be considered not a coincidence of trends, but a real process. In other words, the detected increment in forest cover during the past decades can be considered a regional pattern in the dynamics of vegetation cover in the south of the forest–steppe of the Central Russian Upland.

The increase in forest cover was accompanied by the increase in the degree of patchiness of forested lands. During the analyzed period, mean square of a single forest massif decreased from 13.0 to 9.2 hectares, which occurred against the background of the growth of the total forest square. At the key areas analyzed, the number of forests increased from 2122 in 1970 to 3975 in 2014, i.e., by 87%. At the same time, the least patchy growth was expressed in the steppe zone, where the mean square of a single forest practically did not change against the background of the overall growth of forest square.

Analysis of the sample from the measured boundaries of linear increments of forests allowed us to obtain quantified values of the distances at which the boundaries of forests were moved, and the rate of changes.

The total experimental sample included 769 measurements on the slopes of northern exposure and 516 on the slopes of southern exposure (Table 2).

Comparison of length increments on the slopes of different exposures, conducted based on the data obtained from the Student's t-test, showed that statistically significant difference in length increments on the slopes of the northern and southern exposure is not evident in areas 1, 2, and 5. Significant differences were found in sections 3 and 4, but the length of increments on the southern slopes was higher in section 3 and on the northern slopes in section 4. Analysis of the total sample from all 5 key areas showed that no significant differences in the length of increments on the slopes of the northern and southern exposures were revealed, with their mean steepness of 4°–5°.

The estimation showed that mean distances over which the boundaries of forests have been moved during 45 years differ significantly in all areas except the 3rd and 4th ones (both located in forest–steppe conditions). The mean distance (for both slopes and exposures) in which occurred the dispersal of the forest boundary on the 1st area, westernmost sector

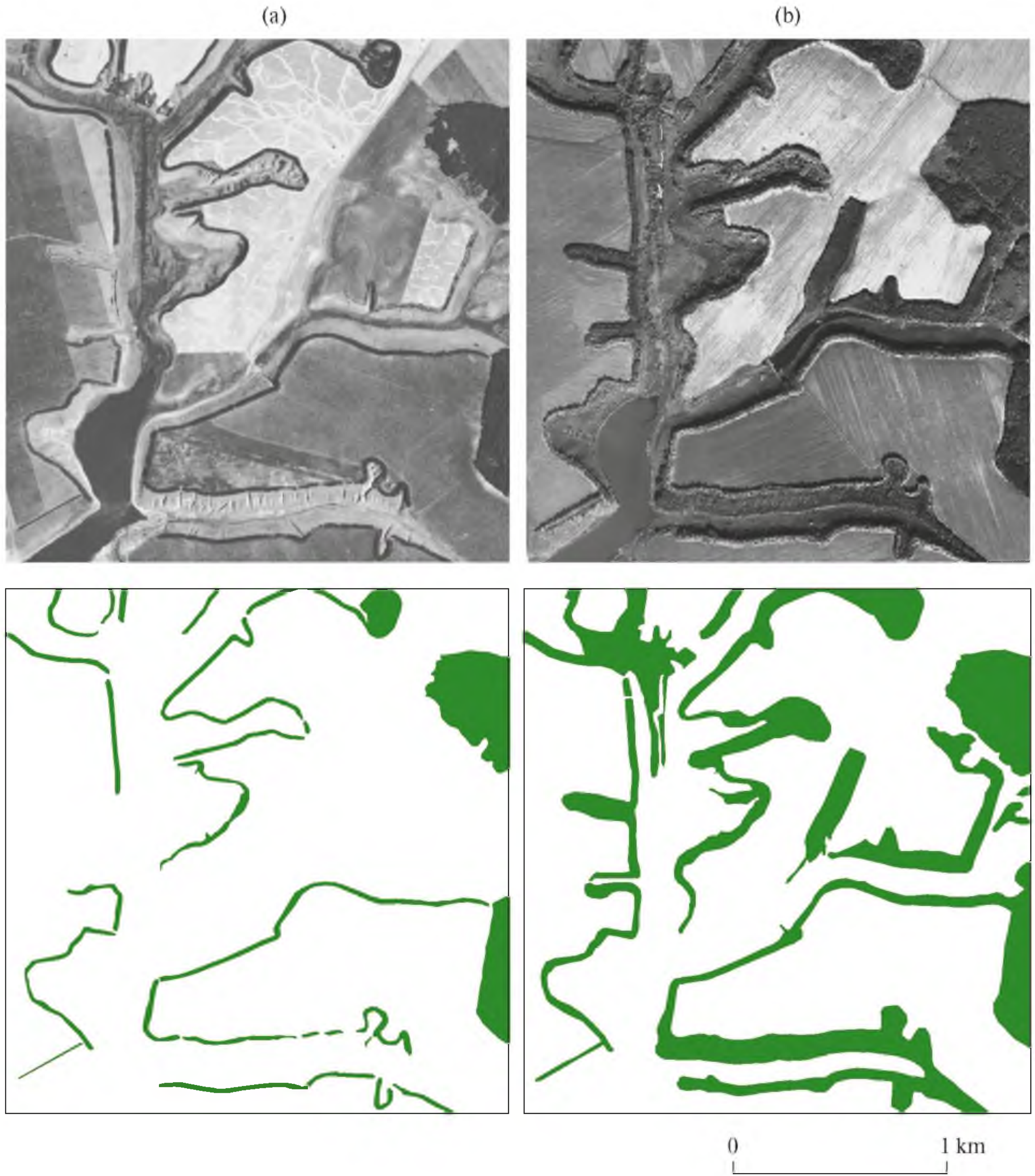

Fig. 2. Example of the change of afforestation on the south of Central Russian Upland from 1970 (a) to 2014 (b) year.

amounted to 34.3 m, 2nd—25.9 m, 3rd—21.2 m, 4th—20.0 m, and 5th (steppe)—15.0 m. Thus, the comparison of increment lengths on key areas, conducted by the method of dispersion analysis, showed that within the region there is a natural decrease in the direction from the west to the east (Fig. 3).

Based on these results, it was found that from 1970 to 2014, the region displayed an increase in forest cover by 31% of its value at the initial estimated date. At the same time, the increment of the forest patchiness was found, which manifests itself in an increase in the number of forests with a decrease in their mean square. The increment in the forest cover was typical both for forest–steppe conditions and for the northern part of the steppe zone. Estimation of distances, which has been advancing the boundaries of forest areas,

Table 2. Parameters of linear increments of forest massifs in 1970–2014 estimated on key areas in Belgorodskaya Oblast

Area	Number of measurements		Mean length of increment, m		Rate, m/10 years	
	northern exposure	southern exposure	northern exposure	southern exposure	northern exposure	southern exposure
1	175	137	33.1	35.9	7.5	8.2
2	147	91	26.9	24.3	6.1	5.5
3	176	115	19.6	23.5	4.4	5.3
4	121	87	24.9	13.3	5.6	3.0
5	150	86	15.1	15.0	3.4	3.4
Totally	769	516	24.0	23.8	5.4	5.4

showed that the highest value of the linear increment of the forests was typical for the western section and composed 34.5 m. The lowest value of the linear increment of the forest boundary was found at the southeastern area, 15 m. This area, unlike others, is located in the northern part of the steppe zone. Statistical estimation showed that there were no significant differences in the distances at which forest boundary moved on the northern and southern slopes.

The increment of the forest cover can be explained by a number of causes. The most important are climatic conditions favorable for the growth of forest cover manifested in the reduction of 10–12 days duration of the winter period, increasing its long-term mean temperature by 1.4–1.6°C and the increase of annual precipitation in the period of 1980–2010 (Lebedeva and Krymskaya, 2008; Novikov et al., 2017). Thus, according to weather stations Belgorod, Valuiki and Bogoroditskoe–Fenino, the increment of annual rainfall in the region during 1980–2010 as compared with an average of many years, was 48 mm.

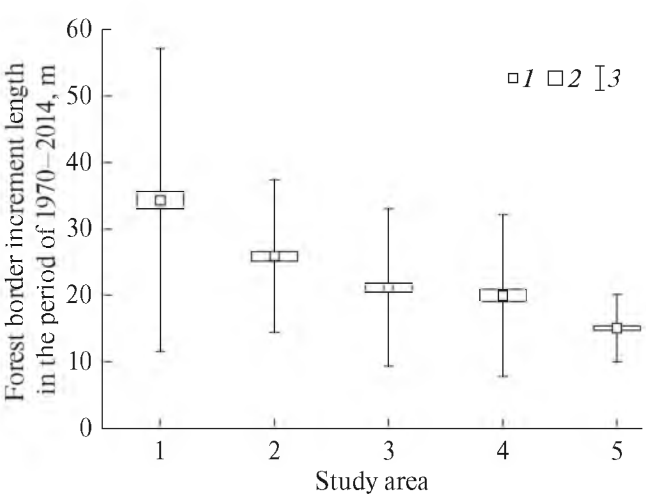

Fig. 3. Characteristics of mean distances of forest massifs movements in the period from 1970 to 2014 on key study areas. (*1*) Mean, (*2*) mean and its standard error, (*3*) standard deviation.

The increment of forest massifs could probably also be facilitated by geomorphological conditions, namely the had developed valley and ravine network redistributing the runoff of precipitation, affecting the nature of ground moisture, and through these the intensity of forest formation. However, this issue requires further special study.

In addition, in some areas the increment of the forest cover may be influenced by the anthropogenic factor, which is fragmentarily manifested in the formation of shelterbelts created along the ravine network heavily developed in the region.

On the territory under study in the same direction, in which there is a decrease in the intensity of linear increments of forest boundaries, there is also a decrease in the values of the hydrothermal coefficient values (Lebedeva and Krymskaya, 2008). Thus, a lower rate of the forest formation in the steppe southeast of Belgorodskaya Oblast may be conditioned by more arid climate of this territory.

CONCLUSIONS

For the south of Central Russian Upland for the period from 1970 to 2014, the increment of the forest cover from 16 to 21% of the total area was found. During the same period, the region showed increased patchiness of forested lands reflected in the increasing number of forest areas (87% of the level in 1970), with simultaneous reduction of the mean area of a singular forest area from 13 to 9.2 ha at the background of the increment of the total area of forested lands. Estimation of distances of the forest border advance between 1970 and 2014 showed that its greatest value is characteristic of the most humid western section of the Belgorodskaya Oblast, and the smallest for the southeastern section corresponding to the steppe zone. The rate of linear increments of forests in the region varied from 7.8 m/10 years in the western part to 3.4 m/10 years in its southeast. Thus, in the study area there was a natural decrease in the rate of linear distribution of forest boundaries from wet to more arid conditions. Alternative exposure of the slopes (southern and northern) in the study region did not have a significant impact on the rate of forest massifs distribution.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors declare that they have no conflicts of interest.

Statement on the welfare of animals. This article does not contain any studies involving animals performed by any of the authors.

REFERENCES

Arkhipova, M.V., Variation in forest area on the Central Russian Upland within the last 250 years, *Contemp. Probl. Ecol.*, 2015, vol. 8, no. 7, pp. 830–837.

Borrelli, P., Modugno, S., Panagos, P., Marchetti, M., Schütt, B., and Montanarella, L., Detection of harvested forest areas in Italy using Landsat imagery, *Appl. Geogr.*, 2014, vol. 48, pp. 102–111.

Chendev, Yu.G., *Evolyutsiya lesostepnykh pochv Sredneursskoi vozvyshennosti v golotsene* (Evolution of Forest-Steppe Soils of Central Russian Plain in Holocene), Moscow: GEOS, 2008.

Kuz'menko, Ya.V., Lisetskii, F.N., Kirilenko, Zh.A., and Grigor'eva, O.I., Ensuring optimal water-conservation forestation in the basin organization of nature management, *Izv. Samar. Nauchn. Tsentra, Ross. Akad. Nauk*, 2013, vol. 15, no. 3-2, pp. 652–657.

Lebedeva, M.G. and Krymskaya, O.V., Modern climate changes in Belgorod oblast, *Nauchn. Ved. Belgorod. Gos. Univ., Ser.: Estestv. Nauki*, 2008, no. 3 (43), pp. 188–196.

Mikhno, V.B., Landscape-related features of oak forests of Central Russian Plain, *Vestn. Voronezh. Gos. Univ., Ser.: Geogr. Geoekol.*, 2012, no. 1, pp. 14–20.

Novikova, E.P., Grigor'ev, G.N., Vagurin, I.Yu., and Chumeikina, A.S., Variations of hydrothermal regime in chernozem zone over last 30 years on the background of global climate change, *Nauchn. Ved. Belgorod. Gos. Univ., Ser.: Estestv. Nauki*, 2017, no. 11 (260), pp. 105–113.

Postolov, V.D., Nedikova, E.V., and Kryukova, N.A., Woodland density and its optimal conditions for Central Chernozem region, *Ekol. Tsentr.-Chernozemnoi Obl., Ross. Fed.*, 2005, no. 2 (15), pp. 95–96.

Potapov, P.V., Zhuravleva, I.V., Manisha, A.E., Turubanova, S.A., and Yaroshenko, A.Yu., Identification and monitoring by remote sensing of global less-disturbed forest territories, *Lesovedenie*, 2008, no. 2, pp. 58–67.

Potapov, P.V., Turubanova, S.A., Tyukavina, A., Krylov, A.M., McCarty, J.L., Radeloff, V.C., and Hansen, M.C., Eastern Europe's forest cover dynamics from 1985 to 2012 quantified from the full Landsat archive, *Remote Sens. Environ.*, 2015, vol. 159, pp. 28–43.

Prirodnye resursy i ekologicheskoe sostoyanie Belgorodskoi oblasti (Natural Resources and Ecological State of Belgorod Oblast), Belgorod: Belgorod. Gos. Univ., 2005.

Schepaschenko, D.G., Shvidenko, A.Z., Lesiv, M.Yu., Ontikov, P.V., Shchepashchenko, M.V., and Kraxner, F., Estimation of forest area and its dynamics in Russia based on synthesis of remote sensing products, *Contemp. Probl. Ecol.*, 2015, vol. 8, no. 7, pp. 811–817.

Schmidt, M., Lucas, R., Bunting, P., Verbesselt, J., and Armston, J., Multi-resolution time series imagery for forest disturbance and regrowth monitoring in Queensland, Australia, *Remote Sens. Environ.*, 2015, vol. 158, pp. 156–168.

Terekhin, E.A., Geoinformation mapping of changes in forests using satellite images (exemplified by Belgorod oblast), *Geogr. Prirod. Resur.*, 2016, no. 4, pp. 174–181.

Ukrainskii, P.A., Terekhin, E.A., and Pavlyuk, Ya.V., Fragmentation of forests of the upper part of the Vorksla River basin in the end of 18th century, *Vestn. Mosk. Univ., Ser. 5: Geogr.*, 2017, no. 1, pp. 82–91.

Zhirin, V.M., Knyazeva, S.V., and Eydlina, S.P., Long-term dynamics of vegetation indices in dark coniferous forest after Siberian moth disturbance, *Contemp. Probl. Ecol.*, 2016, vol. 9, no. 7, pp. 834–843.

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