

Article

# The Influence of Relief on the Density of Light-Forest Trees within the Small-Dry-Valley Network of Uplands in the Forest-Steppe Zone of Eastern Europe

Pavel Ukrainskiy <sup>1</sup>, Edgar Terekhin <sup>1</sup>, Artyom Gusarov <sup>2</sup> , Eugenia Zelenskaya <sup>1</sup> and Fedor Lisetskii <sup>1,\*</sup> 

<sup>1</sup> Federal–Regional Center of Aerospace and Surface Monitoring of the Objects and Natural Resources, Belgorod National Research University, 308015 Belgorod, Russia; pa.ukrainski@gmail.com (P.U.); terekhin@bsu.edu.ru (E.T.); zelenskaya@bsu.edu.ru (E.Z.)

<sup>2</sup> Institute of Geology and Petroleum Technologies, Kazan Federal University, 18 Kremlyovskaya Str., 420008 Kazan, Russia; avgusarov@mail.ru

\* Correspondence: liset@bsu.edu.ru; Tel.: +7-4722-301370

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**Abstract:** An active process of the invasion of woody vegetation, resulting in the formation of light forests, has been observed in predominantly herbaceous small dry valleys of the forest-steppe uplands of the East European Plain over the past two decades. This paper investigates the spatial features of the density of trees in such light forests and its relationship with relief parameters. The Belgorod Region, one of the administrative regions of European Russia, was chosen as a reference for the forest-steppe zone of the plain. The correlation between some relief characteristics (the height, slope, slope exposure cosine, topographic position index, morphometric protection index, terrain ruggedness index, and width and depth of small dry valleys) and the density of light-forest trees was estimated. The assessment was carried out at the local, subregional and regional levels of generalization. The relief influence on the density of trees in the small dry valley network is manifested both through the differentiation of moisture within the territory under study and the formation of various conditions for fixing tree seedlings in the soil. This influence on subregional and regional trends in the density is greater than on local trends. The results obtained are important for the management of herbaceous small-dry-valley ecosystems within the forest-steppe uplands in Eastern Europe.

**Keywords:** trees invasion; trees mapping; smooth interpolation; multiscale patterns; spatial trend; geomorphometric features; correlation analysis; Central Russian Upland; Belgorod Region

## 1. Introduction

Over the recent 20 years, there has been an active invasion of tree vegetation into the herbaceous ecosystems in the southwestern part of the European territory of Russia (hereinafter, European Russia) [1]. This process in the region can be associated both with current climate change [2] and a decrease in the area of pastures and hayfields due to significant changes in agriculture that followed after the collapse of the Soviet Union at the end of 1991 [3].

The expansion of tree vegetation into grasslands was (and is) widely observed in different regions of the world: in the North American prairies [4–7], South American pampas [8–10], Eurasian steppes [11], and subalpine meadows of Europe and North America [12–15], and so forth. A specific feature of the forest-steppe in the southwestern part of European Russia is the dispersal of tree vegetation along the small dry valley network that has a significant density there and, therefore, has an impact both on the formation of local landscapes and the features of their economic use.

A small dry valley (*bálka* in Russian terminology) is a dry (or with a temporary snowmelt-induced or rainfall-induced water stream) valley with soddy slopes. It has a gently concave bottom, often without a noticeable channel; the slopes are convex, smoothly turning into watersheds. The lengths of small dry valleys are usually from hundreds of meters to 20–30 km, the depths are from several meters to tens of meters, and the widths are up to hundreds of meters. The relatively small size and the absence of a permanent watercourse at the bottom of small dry valleys is one of the diagnostic features that distinguish them from typical river valleys.

Within this territory, tree vegetation can be resettled from time to time by increasing the area of artificial windbreaks, as well as the advancement of the boundaries of natural forests [1]. In other cases, independent light forests are formed in the small dry valley network. They can be both permanent plant communities and a successional stage in the formation of closed forest communities.

Existing works on the study of the invasion of tree vegetation into herbaceous ecosystems of Russia mainly concern the distribution of tree (woody) vegetation on abandoned arable lands [16–19]. However, in the southwestern part of European Russia, the spread of abandoned arable land is small as compared to the rest of the territory, and fallow lands are rare [20–23]. At the same time, the small dry valley network is widespread there, and it is the main reserve of territories for the resettlement of tree vegetation — so-called light forests (or open woodlands). The light forests growing in the network have remained poorly studied up to the present time. This is especially true for their modern temporal dynamics. Studies in other regions of the world have shown that relief (topography) affects the tree density in these light forests [24–27] and, therefore, determines many aspects of their ecological development and economic use.

The aim of the study is to reveal the influence of relief characteristics on the spatial patterns of changes in the density of trees in light forests in the uplands of the forest-steppe of Eastern Europe. The implementation of this aim was carried out on the example of the southwestern part of European Russia within the Belgorod Region. To achieve this aim, the following tasks were solved:

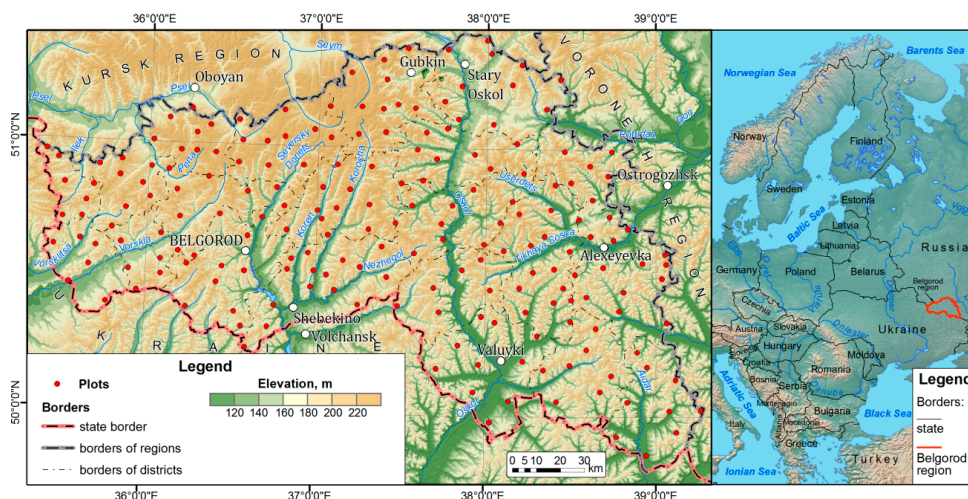
- Collection and systematization of information on tree density in light forests.
- Analysis of changes in the density of trees in light forests in the Belgorod Region.
- Correlation analysis between the relief characteristics of the small dry valley network and the density of trees in light forests of the region.
- Determination of those relief characteristics that have a predominant influence at different territorial levels of the study: local, subregional, and regional.
- Interpretation of the revealed patterns.

## 2. Materials and Methods

### 2.1. Study Area

The territory under study is the Belgorod Region. This administrative region of Russia is located in the southwest of its European part, near the border with Ukraine (Figure 1). The area of the region is 27,100 km<sup>2</sup>.

The Belgorod Region is situated in the southern part of the Central Russian Upland, one of the largest uplands in the East European Plain. The upland's surface is a hilly plain, dissected by a relatively dense network of river valleys, small dry valleys, and gullies. The total length of the small dry valleys network of the region is estimated at 18,500 km, while the total length of the entire erosional network, including river valleys, is 22,500 km (based on SRTM Void Filled data (version 3.0 with spatial resolution 3 arc second)). The entire erosional network's density increases from 1.0–1.5 km/km<sup>2</sup> in the northwest to 1.8–2.0 km/km<sup>2</sup> in the southeast of the region [28]. The general slope of the surface of the region's territory is directed to the south. The maximal absolute height is 277.2 m, the minimal is 68.3 m.



**Figure 1.** The territory under study (the Belgorod Region) with the location of registration plots.

According to the Köppen climate classification [29], the Belgorod Region has a climate Dfb—a humid continental climate with warm summers. Air temperatures within the region gradually increase from north to south: the average annual temperature varies there from  $+6.3\text{ }^{\circ}\text{C}$  to  $+7.5\text{ }^{\circ}\text{C}$ , the average January temperature from  $-6.9\text{ }^{\circ}\text{C}$  to  $-5.8\text{ }^{\circ}\text{C}$ , respectively (estimates for the period 1973–2013 by [30]), and the average July temperature from  $+19.4\text{ }^{\circ}\text{C}$  to  $+20.7\text{ }^{\circ}\text{C}$  [31].

Annual precipitation decreases from the northwest to the southeast of the Belgorod Region from 663 to 614 mm (estimates for the period 1973–2013, according to [32]). Sixty-three percent of the annual precipitation occurs during the warm season (the maximum quantity is in June and July). Snow cover usually forms in December and melts in March. Its depth at the end of winter is most often 20–30 cm. The duration of the snow cover is 100–120 days [31,33].

The Belgorod Region belongs predominantly to the forest-steppe zone of the East European Plain. Before the start of economic development, the steppes growing on chernozem soils occupied most of its territory. The steppes were interspersed with oak forest patches growing on gray forest soils. *Acer platanoides* L., *Tilia cordata* Mill., *Fraxinus excelsior* L., and elms also currently grow in oak forests, along with *Quercus robur* L. Pine forests grew (and grow) on sandy riverine terraces. By now, almost all steppes that were widespread there in the 17th century have been ploughed up. In addition, by now, two-thirds of the forests that grew there in the 17th century have been cut down, and then soils beneath them have also been ploughed up [34]. The ecological specificity of forests in the forest-steppe and steppe environments is well-diagnosed by differences in the rate of pedogenesis [35]. By now, cultivated lands occupy about 60% of the region's territory, while about 12% of its area is still forested. Pastures and hayfields, which occupy 17% of the region's territory, are concentrated mainly in the small dry valleys network, as well as in river valleys.

The object of the study (within the Belgorod Region) is the small dry valleys network prevailed by herbaceous steppe vegetation [36]. However, small-sized wooded areas can be also located in the upper parts of the network. The economic use of small dry valleys in the region is represented by haymaking and grazing [3]. The network is usually surrounded by croplands. In many cases, small dry valley systems are fringed by (woody) windbreaks, most of which were created by humans in the 1960s [37]. Thus, artificial windbreaks are often located at the border of croplands and small dry valleys. At present, light forests are widespread throughout the small dry valleys network. In most cases, these are plots with an area of up to several tens of hectares. The species composition of the light forests in the Central Russian Upland basically includes wild fruit trees and shrubs—apple trees, pear trees, hawthorn, and wild rose [38]. From time to time, some forest species can penetrate into the light forests from the nearby indigenous forests and artificial windbreaks. Normally, there are elms, *Acer platanoides* L. and *Acer tataricum* L., *Fraxinus excelsior* L., and, occasionally, *Quercus robur* L.

in the light forests. Some alien species (*Robinia pseudoacacia* L. and *Acer negundo* L.) are also actively introduced into the light forests [39,40].

## 2.2. Source Materials

The light forests growing in the small dry valleys network of the Belgorod Region were studied using ultra-high spatial resolution satellite images. We used mosaics of space images provided by web mapping services, primarily by Google Earth. The images were analyzed using the QGIS 3.10 software [41]. The plugin QuickMapServices was used.

The sections of the small dry valleys network with growing light forests were selected by a visual analysis of remote-sensing data. All areas with forest vegetation, the crowns of which do not close together, are categorized as light forests. That is, free-standing trees are clearly visible against the background of grass. A rectangular area of 1 hectare was allocated on these territories. The plots were prepared in a vector layer with polygonal geometry. The sides' sizes of the plot were  $100 \times 100$  m or  $50 \times 200$  m, depending on the shape and size of a particular section of the small dry valleys network. A total of 200 plots were identified (see Figure 1). The location of the plots was predetermined by the structure of the small dry valleys network and the presence of light forests in it. The light forests do not have continuous distribution in the small dry valleys network. They are found as separate fragments. The plots are confined to these fragments.

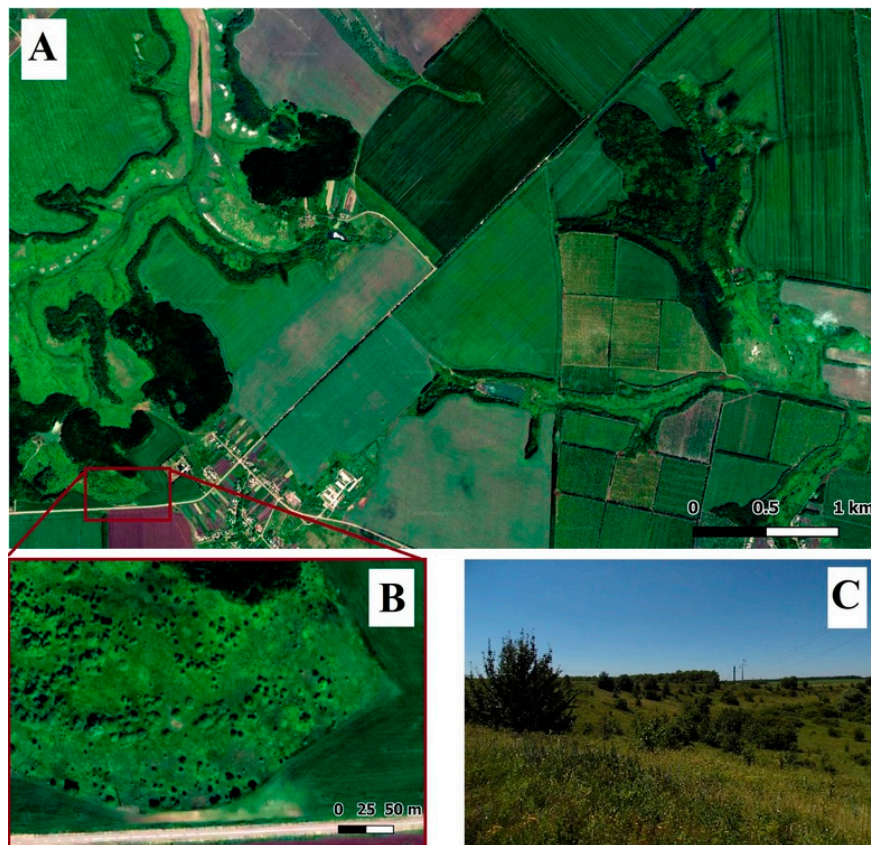
To select the plots (sites), light forests were selected in such a way that the uniformity of their distribution over the territory of the Belgorod Region was ensured. The Clark-Evans test [42] was used to meet this requirement. The test was performed in the R statistical environment using the spatstat add-on package [43,44]. The test variant with boundary correction was also used. According to the test results, the value of the Clark-Evans test  $R$  was 1.44 ( $p = 0.002$ ). This indicated a statistically significant deviation of the area distribution from the random spatial distribution. Since the criterion value was greater than 1.0, the distribution was uniform (for values less than 1.0, this would be the group distribution).

The light forest areas, in which 200 sites (plots) were established, have an area of 2 to 63 hectares (on average, 11 hectares). The distance between the nearest sites ranged from 4.0 to 17.4 km (on average, 8.9 km; the standard deviation was 2.5 km).

All trees within each plot were manually vectorized in a point feature layer (Figure 2). Individual trees were identified using mosaics of images with ultra-high spatial resolution (more detailed 1 m/pixel). That is, the size of the crowns of individual trees was always somewhat larger than the pixel size of the mosaic images. All satellite data used were obtained during the active growing season. Due to the relatively small area of the region studied, the phenological phases differed insignificantly within its limits. Due to taking into account the listed criteria, the obtained experimental data can be considered objective.

After vectorization, the density of trees was calculated for each plot and entered into the attribute table of the polygonal layer of the plots. The study of the density of trees in the regional light forests was carried out without differentiating them by species composition.





**Figure 2.** An example of light forests in satellite images and on the ground: (A) Small dry valley general view with a light forests. (B) Small dry valley fragment with a light forest. (C) Light forest's ground photography (typical light forest near the village of L'vovka, east of the Belgorod Region).

The following group of variables was studied to estimate the relief's effect on the density of trees in light forests: the absolute height, slope, aspect, topographic position index (TPI), profile curvature, morphometric protection index (MPI), terrain ruggedness index (TRI), and width and depth of small dry valleys (see Table 1). When analyzing the relief's characteristics, we used a digital elevation model (DEM) with a spatial resolution of 30 m/pixel [45]. This DEM was used to construct raster models of the derived relief's characteristics. Relief characteristic values (except for the width and depth of the small dry valleys) were ArcGIS-computed for each study plot. For this, a zonal statistics tool was used; that is, an average value was calculated for all pixels within the plot.

Besides the relief characteristics, this paper analyzed the nontopographic features (see Table 1), which can demonstrate the impact produced by the climate, the practical use of a small dry valleys, and the location of tree seed import sources. The significance of the relief for the development of light forests in the small dry valley network can be described in more detail by comparing correlations with relief-related tree density and nontopographic features.

**Table 1.** Analyzed factors affecting the density of trees in light forests. DEM: digital elevation model, MPI: morphometric protection index, and TRI: terrain ruggedness index [3,45–54].

Characteristics	Units	Source of Initial Data for Development	Software for Initial Data Processing	Development Description	
Relief characteristics					
Absolute height	m	DEM from the paper by Buryak et al., 2019 [45]	ArcGIS	Ready-made DEM was used	
Slope	degree		ArcGIS	Slope raster were acquired in ArcGIS 10.5 using standard Spatial Analyst tools.	
Aspect	-		ArcGIS	The slope exposure (aspect) was converted to cosine for further use in statistical analysis. The analysis methods we used are designed to work with continuous data, while the aspect is circular data. Cosine transform allows creating the continuous data from circular data [46]. To do this, first an aspect raster with values in degrees was created in ArcGIS 10.5 software. Then, the aspect values were converted into radians using the Map Algebra tool, and the cosine of these values was calculated. The aspect cosine ranges from 1.0 for north to −1.0 for south. It shows how much the real value of the aspect differs from the north aspect. Therefore, the aspect cosine is called “northness” [47].	
TPI	-		ArcGIS and Land Facet Corridor [49]	The topographic position index (TPI) indicates which part of the slope a point is located in [48]. Positive index values indicate a position above the midpoint of the slope, negative values below the midpoint of the slope. The TPI is calculated as the difference between the height of a point and the average height in a certain search radius [50]. A search radius of 1000 m was used to calculate the TPI. The TPI was calculated in a standardized way; that is, it divided by the standard deviation of heights in the search radius.	
Profile curvature	m <sup>−1</sup>			Profile curvature raster were acquired in ArcGIS 10.5 using standard spatial analyst tools.	
MPI	-			SAGA [51]	The algorithm analyzes the immediate surroundings of each DEM pixel in a given search radius and estimates how much the relief protects this point from the surrounding terrain. This is equivalent to positive openness [52]. The MPI was also calculated with a search radius of 1000 m.
TRI	-			SAGA [51]	TRI shows how large a difference in elevation is observed at a particular point in the terrain. It was calculated by determining the difference in heights between a specific DEM pixel and its eight immediate neighbors (the calculation was carried out in a sliding window of 3 × 3 pixels). Then the mean of these differences squares was calculated. The square root of this mean is the TRI [53].

Table 1. Cont.

Characteristics	Units	Source of Initial Data for Development	Software for Initial Data Processing	Development Description
Width of small dry valleys	m	Mosaics of space images from ESRI World Imagery	ArcGIS	The small dry valley width was measured directly at those locations of the sites where the trees were vectorized. For this, a linear layer was created in which lines were drawn across small dry valleys: the lines were drawn from edge to edge, crossing the site. The small dry valley widths were calculated as the lengths of these lines. The geometry calculation tool in the layer's attribute table was used for this. The small dry valley depths were measured as the difference between the minimal (along the thalweg line) and maximal heights within this line. For this purpose, such an indicator of zonal statistics as range of values was extracted from the DEM along the line using ArcGIS 10.5 software.
Depth of small dry valleys	m		ArcGIS	
Non-topographic features				
Hydrothermal index (HTI)	-	Lebedeva et al., 2019 [54]	ArcGIS	A raster was interpolated along the contour lines plotted by the authors. Zonal statistical values extracted from the raster.
A distance to the nearest windbreaks or forest	km	The layer of forests (authors data) The layer of windbreaks (authors data)	ArcGIS	The nearest object standard tool used.
The area of the nearest forest	ha	The layer of forests (authors data)	ArcGIS	The nearest object standard tool used.
Density of windbreaks	km/km <sup>2</sup>	The layer of windbreaks (authors data)	ArcGIS	The density of windbreaks was calculated for the Thiessen polygons constructed around the sites
Share of unused pastures and hayfields split by municipalities	%	Kitov, 2015 [3]	ArcGIS	Values to be taken from WMS available layer <a href="https://qgiscloud.com/deppriroda/cons/wms">https://qgiscloud.com/deppriroda/cons/wms</a>

### 2.3. Research Methods

We performed all statistical data analyses in the statistical computing environment R 3.4.4 [43]. Smoothing interpolation was used to create tree density change maps for the light forest located in the territory of the Belgorod Region. The interpolation was performed in the R statistical computing environment with the use of the optional spatstat package [44]. The Smooth function of this package implements a smoothing interpolation. It is based on the calculation of the locally weighted average using the Nadaraya-Watson formula [55,56]. The kernel type and the presence of boundary correction are the key settings for the interpolation process performed by the Smooth search radius function. We used a Gaussian kernel and boundary correction, as previously suggested by Diggle [57]. Using this interpolation, we could obtain several rasters created with different search radii (5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 km). With the search radius being increased, the generalization of the resulting maps can be improved. This makes it possible to identify trends in tree density at different scale levels. This approach is based on the concept of the poly-scale organization of landscapes [58–62]. We considered three large-scale levels: local, subregional, and regional. In our case, the regional level covers the territory of the entire Belgorod Region. It corresponds to search radii of 40–50 km. The subregional level covers individual physical geographic districts of the region and their parts. It corresponds to search radii of 15–25 km. The local level is reduced to individual local landscapes within the physical geographic districts of the region. It corresponds to a search radius of 5 km. The Smooth function can return not only a bitmap but, also, local mean values at the original points. For each search radius, we calculated the local average density of trees in light forests. The obtained values were used in the correlation analysis.

The correlation between the density of trees in light forests and the above relief's variables has been estimated in the study. Initial density values and local mean values obtained from ten different search radii were used to calculate the correlation. The correlation between various variables of the relief was also calculated. Using the cor.test function, Spearman's correlation coefficients were also calculated. The Spearman's Rank correlation coefficient [63] was used due to the fact that the analyzed indicators have a distribution that differs from the normal one. The normality of the distribution was assessed with the Shapiro-Wilk test [64] (the R function shapiro.test).

## 3. Results and Discussion

### 3.1. Changes in the Density of Trees in Light Forests of the Belgorod Region

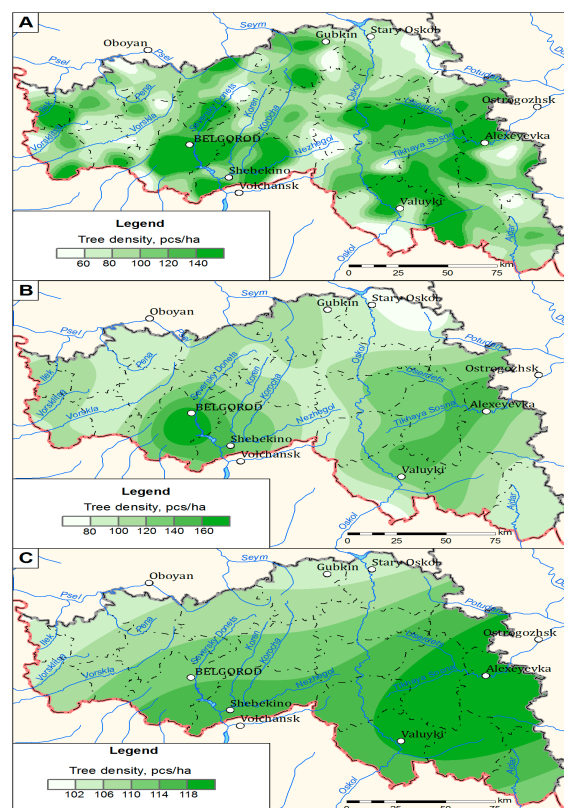
Table 2 shows the estimated tree densities obtained for different search radius values in the smoothing interpolation. A zero search radius means the initial raw data—the number of trees counted on the sites.

The resulting maps of the density of trees in light forests for the local, subregional, and regional levels are shown in Figure 3. A variegated pattern of changes in the density of trees in light forests is observed at the local level, since there are high and low values of this density in any part of the Belgorod Region. At the same time, the transition from high values to low ones in the most cases occurs at a distance of only 25–30 km. Areas with high and low tree density values at the local level include three to ten sites. There are some areas, representing high-spatial and low-spatial outliers. High outliers are sites with high tree density values, all neighbors of which have low values. Low outliers are areas with low tree density values, all neighbors of which have high values.



**Table 2.** The density of trees (pcs. per ha) in light forests, estimated for various search radii of the smoothing interpolation.

Search Radius, km	Minimum	Mean	Median	Maximum	Standard Deviation
0	21.00	111.15	99.00	415.00	62.70
5	40.20	115.19	106.86	370.51	46.74
10	49.82	112.33	107.49	206.02	26.53
15	61.23	112.46	107.29	165.75	19.93
20	75.81	112.78	108.31	154.28	16.28
25	82.80	112.92	110.57	146.11	13.37
30	88.77	112.99	113.09	138.10	10.97
35	93.89	113.01	113.08	130.99	9.05
40	97.30	112.00	113.07	127.50	7.56
45	99.06	112.95	112.82	125.65	6.41
50	100.56	112.88	112.96	123.92	5.53



**Figure 3.** The density of trees in light forests at the local ((A), search radius 5 km), subregional ((B), search radius 15 km), and regional ((C), search radius 50 km) scale levels of generalization within the Belgorod Region, SW Russia.

In contrast to the local level, you can notice clearly expressed territorial patterns at the subregional level. From west to east, there is an alternation of areas with an increased and decreased density of trees. However, spatial outliers of high or low values at the subregional level are not detected. The reasons for the formation of such a tree density geography in the light forests at the subregional level need to be studied additionally within the framework of separate research. We assume that, for the two areas with the highest values of the density of trees, the leading formation factors are

different. The formation of such an area around the city of Belgorod is associated with the low intensity of the economic use of the small dry valleys network there. According to existing estimates, more than 75% of natural forage lands are not used around the city [3]. The lack of grazing and haymaking creates favorable conditions for the settlement of forest vegetation in the small dry valleys network.

In the area of high tree density along the Valuyki-to-Alexeyevka line (see Figure 3), the share of unused natural forage lands is also increased, although to a lesser extent than around the city of Belgorod. There, the share of unused natural grasslands reaches 70–90% and, in the vicinity of Belgorod, it is 85–95% [3]. However, this factor is reinforced by the presence of powerful sources for the import of seeds of forest plants: to the north of the towns of Valuyki and Alexeyevka (see Figure 3), there are wooded areas that are one of the largest forestlands in the Belgorod Region. Many small dry valleys are located next to them, and some of the valleys begin right in the forestlands. Areas of increased density of trees in light forests (more than 100 trees per hectare) mainly cover the middle and lower parts of the basins of large rivers of the Belgorod Region. There are three such areas in total in the region. The western area is the lower part of the Vorskla River basin, as well as the basins of the Vorsklitsa River and Ilek River. This area includes 16 plots. The density there is 100–110 trees per hectare. The central area is the lower parts of the basins of the Seversky Donets River and Nezhegol River. This area includes 41 plots. The density there is 100–180 trees per hectare. The eastern area is the basins of the Tikhaya Sosna River and Userdets River (see Figure 3A). This area includes 66 plots. The density there is 100–145 trees per hectare.

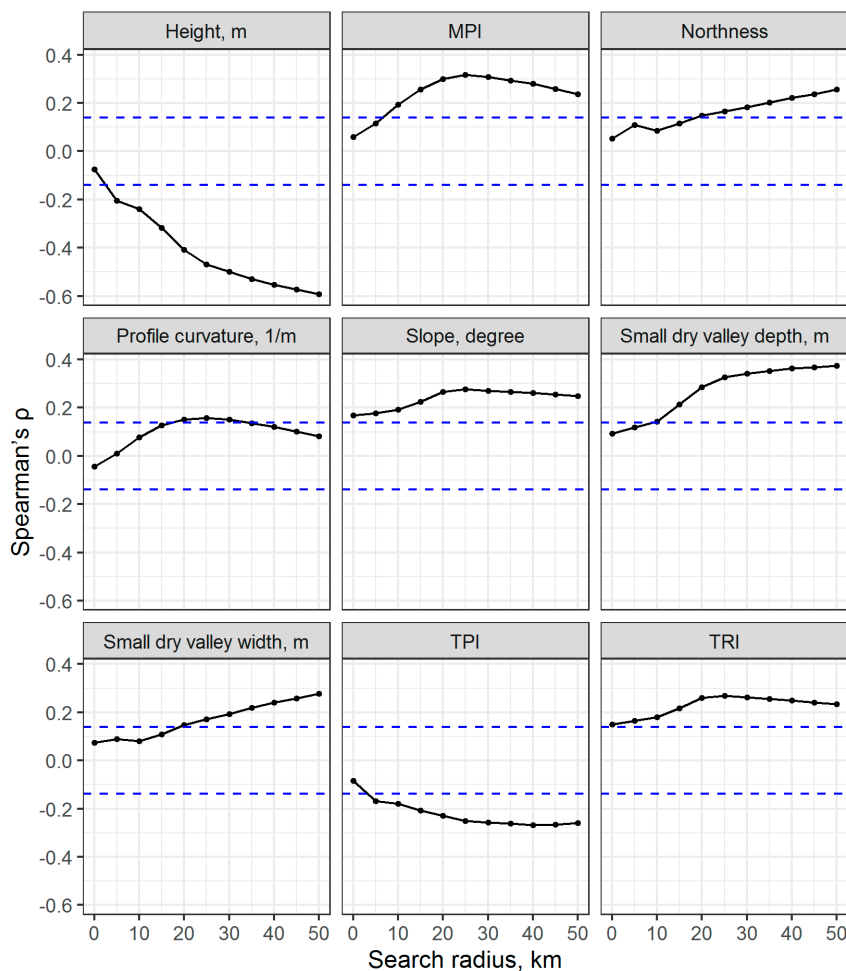
Areas of low tree density in light forests (less than 100 trees per hectare) at the subregional level are confined to the largest river's interfluves, as well as to the upper parts of their basins. There are three such sites in the region. The largest of them is situated in the center of the Belgorod Region and covers the interfluve of the Seversky Donets River and Oskol River, as well as the upper parts of the basins of the Oskol, Seym, Nezhegol, Koren, and Korocho Rivers (see Figure 3B). This area includes 42 plots. A decrease in the density of trees in light forests is observed there from south to north. In this direction, the density decreases from 110 to 80 trees per hectare. Two more areas of low tree density in light forests are located in the southeastern (the Aidar River basin) and the northwestern (the interfluves of the Vorskla River, Psel River, and Pena River) parts of the Belgorod Region (see Figure 3B). The first area includes nine plots and the second one, 23 plots. In the southeastern area, the density in open woodlands is 90–100 trees per hectare and, in the northwestern area, 80–90 trees per hectare.

At the regional level, there is no alternation of areas of high and low density of trees. Instead, there is a unidirectional increase in tree density in the open woodlands from 100–102 to 118–124 trees per hectare. This increase occurs in the direction from northwest to southeast. Its maximal values are reached in the interfluve area of the Tikhaya Sosna, Oskol, and Aidar Rivers (see Figure 3C). As well as at the subregional level, there are no spatial outliers of high or low values of the density of trees in light forests at the regional level of the study.

The absolute height of the base surfaces (that is, the height of small dry valley bottoms) decreases from the northwest to the southeast of the Belgorod Region (from 170–200 m to 90–120 m), and the vertical dissection of the topographic surface increases from 30–40 m to 70–80 m, respectively [28]. At the same time, the availability of groundwater for forest vegetation increases in small dry valleys. As stated earlier, from the northwest to the southeast of the Belgorod Region, air temperatures also increase, while the annual precipitation decreases [28]. These circumstances impede the spread of forest vegetation in the indicated direction. The geography of the density of trees observed at the regional level shows that favorable geomorphic conditions in the small dry valleys network compensates for the unfavorable climatic conditions there. For the forest-steppe and steppe zones, this was noted earlier, but on the example of the existence of small-dry-valley dense forests (bairak forests in Russian terminology—forests that grow in small areas on the tops and slopes of small dry valleys in the steppe and forest-steppe zones) [65]. In our study, we observed a new form of this regularity manifestation by the example of light forests.

### 3.2. Correlation of Tree Density and Relief Characteristics

The values of the local average density of trees obtained with different search radii have different strengths of relationships with the relief (Figure 4). According to this connection’s form, the relief characteristics can be divided into three groups. The first group is those variables that have a negative correlation with the density of trees (absolute height and the topographic position index). With an increase in the search radius, the strength of a relationship for these variables increases. The second group consists of those variables that have a positive correlation with the density of trees (the aspect “northness”, width, and depth of small dry valleys). With an increase in the search radius, the strength of a relationship between these variables also increases.



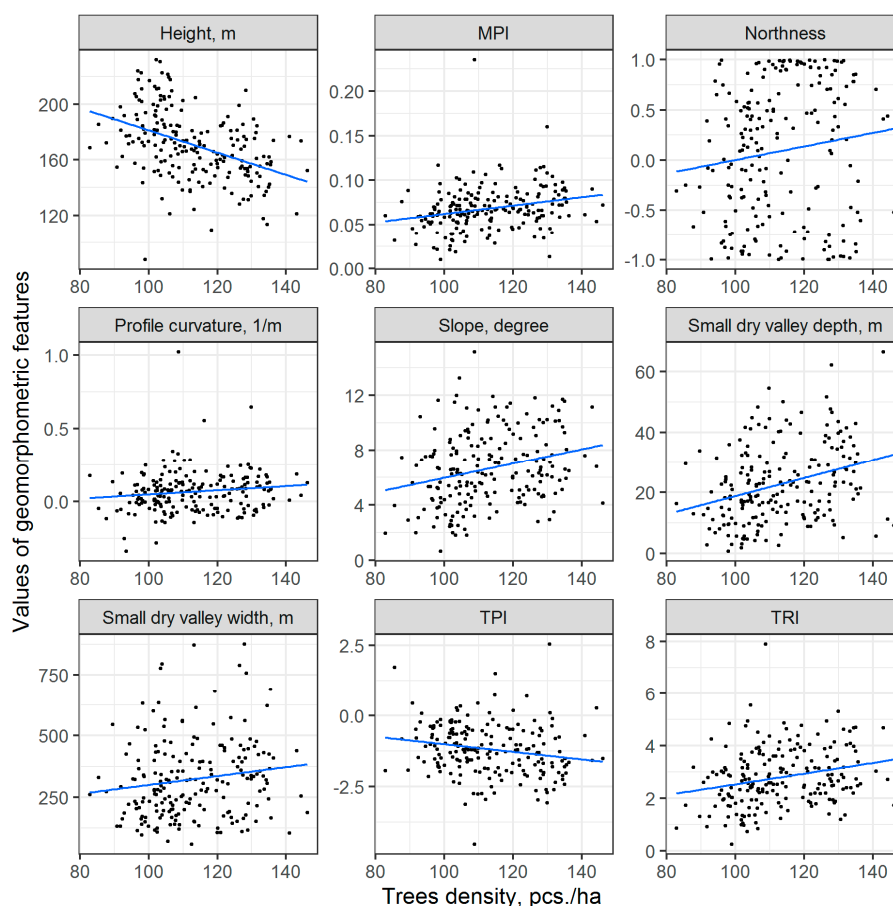
**Figure 4.** Changes in the correlation coefficient between the density of trees and the studied relief characteristics with an increase in the search radius with the smoothing interpolation (statistically significant ( $p < 0.05$ ) correlations are above and below the blue dotted line). MPI: morphometric protection index, TRI: terrain ruggedness index, and TPI: topographic position index.

The third group includes the relief characteristics that also show a positive correlation with the tree density (the morphometric protection index (MPI), terrain ruggedness index (TRI), profile curvature, and aspect). However, with search radius being increased, the relationship strength first increases (up to a search radius of 25 km) and then decreases. This can be due to complication of the interrelationships between factors because of the transition to another hierarchical level of the landscape structure.

At the local level, the lowest correlation between the relief and the density of the trees can be observed. For all relief characteristics studied, except for the slope and terrain ruggedness index (TRI),

the Spearman’s correlation coefficients are statistically insignificant for search radii up to five km. Based on this, it can be assumed that, at the local scale level, the relief is not the leading factor in the formation of light forests in small dry valleys of the region. The location of tree the seed import sources [39,40] and the nature of the economic use (grazing and haymaking, as well as grass burning) of the small dry valleys network [3] can be of great importance in the local level. However, this requires separate research.

For four of the considered relief characteristics (the aspect, morphometric protection index MPI, terrain ruggedness index TRI, and profile curvature), the maximal correlation with the density of the trees is achieved at a search radius of 25 km. The same can be said about the depths of small dry valleys. Although it shows a growing correlation at search radii of more than 25 km, this growth is already insignificant. Thus, the slope, MPI, TRI, profile curvature, and the depths of small dry valleys have the greatest influence on the density of the trees at the subregional level of the study. The shapes of the correlation fields for a search radius of 25 km are depicted in Figure 5.



**Figure 5.** The relationship between the studied relief characteristics and the density of trees in light forests with a search radius of 25 km in a smoothing interpolation.

For the additional four relief characteristics (the slope, north aspect, TPI, and small dry valley width), the maximal correlation with the density of the trees can be achieved with a search radius of 50 km. The influence of these characteristics prevails at the regional level.

Table 3 demonstrates the intercorrelation of the relief characteristics. The obtained correlation matrix shows that it is potentially possible to abandon the use of the TRI, since it has a correlation with the slope factor of 0.99. The rest of the indicators are less related to each other (absolute values of the correlation coefficients are not more than 0.75), but each is of interest separately.

**Table 3.** Correlation matrix for the relief variables studied.

Relief Variables	Height	Slope	Northness	TPI	Small Dry Valley Width	Small Dry Valley Depth	TRI	MPI	Profile Curvature
Height	<b>1.00</b>	<b>-0.22</b>	<b>-0.28</b>	<b>0.47</b>	<b>-0.21</b>	<b>-0.29</b>	<b>-0.23</b>	<b>-0.38</b>	<b>-0.21</b>
Slope	<b>-0.22</b>	<b>1.00</b>	<b>0.27</b>	-0.03	<b>0.35</b>	<b>0.55</b>	<b>0.99</b>	<b>0.46</b>	<b>-0.22</b>
Northness	<b>-0.28</b>	<b>0.27</b>	<b>1.00</b>	-0.19	<b>0.25</b>	<b>0.29</b>	<b>0.27</b>	0.18	0.06
TPI	<b>0.47</b>	-0.03	-0.19	<b>1.00</b>	-0.08	<b>-0.21</b>	-0.05	<b>-0.62</b>	<b>-0.60</b>
Small dry valley width	<b>-0.21</b>	<b>0.35</b>	<b>0.25</b>	-0.08	<b>1.00</b>	<b>0.75</b>	<b>0.33</b>	<b>0.21</b>	<b>-0.21</b>
Small dry valley depth	<b>-0.29</b>	<b>0.55</b>	<b>0.29</b>	<b>-0.21</b>	<b>0.75</b>	<b>1.00</b>	<b>0.55</b>	<b>0.42</b>	-0.11
TRI	<b>-0.23</b>	<b>0.99</b>	<b>0.27</b>	-0.05	<b>0.33</b>	<b>0.55</b>	<b>1.00</b>	<b>0.51</b>	-0.18
MPI	<b>-0.38</b>	<b>0.46</b>	0.18	<b>-0.62</b>	<b>0.21</b>	<b>0.42</b>	<b>0.51</b>	<b>1.00</b>	<b>0.60</b>
Profile curvature	<b>-0.21</b>	<b>-0.22</b>	0.06	<b>-0.60</b>	<b>-0.21</b>	-0.11	-0.18	<b>0.60</b>	<b>1.00</b>

NB: The statistically significant ( $p < 0.05$ ) correlation coefficients are highlighted in bold.



As regards the insufficient humidification in the Belgorod Region (especially in its southern and southeastern parts), the humidification degree is the main limiting factor for the development of forest vegetation. The diversity of small dry valley network topography leads to a variety of microclimates and determines the variations of moisture conditions. The closer the aspect (slope exposure) is to the northern direction, the better the conditions for humidification of slope landscapes, primarily due to the lower insolation heating [66]. In the warm season, less moisture evaporates on such slopes. This pattern is especially noticeable in the temperate latitudes of Earth. In addition, on north-oriented slopes, the snow lingers longer in the spring, and its melting occurs relatively slower [67]. Slopes with a concave profile provide a concentration of surface water runoff, while slopes with a convex profile disperse the runoff. Therefore, the lower the value of the profile curvature, the better, with other things being equal, such as the moistening of the soil [68]. Consequently, more favorable conditions for tree growth are formed.

In the Belgorod Region, it is the absolute height and the related relief characteristics (the topographic position index and small dry valley depth) that determine the distance from the ground surface to the nearest aquifer, which also feeds tree roots with water and substances dissolved in it. Therefore, the lower a plot is located from a geomorphological point of view, the better, other things being equal for the conditions for tree growth there.

The slope and TRI are related to ground surface erosional features. The larger these variables, the more small-dry-valley slopes are eroded, other things being equal. With increasing the slope and TRI, the number of gullies (including side gullies) increases. The erosional microrelief helps the trees to be fixed, since the existing areas of bare soil/ground allow tree seedlings not to compete with grassy vegetation. Moreover, the increased snow accumulation, usually observed in gullies and small side hollows, increases the moisture content of the soil and ground in the spring (snowmelt) season [67]. In addition, areas with steep slopes and an abundance of gullies are of little use for farming. Haymaking and cattle grazing are also difficult within them.

### 3.3. The Impact Produced by Nontopographic Factors on Tree Density in Light Forests

In addition to the relief, the location of tree seed import sources can produce an impact on the density of trees in light forests. At the local level, you can observe a significant correlation related with the distance from potential sources of forest species introduction (distance to the nearest forest or windbreaks)—Spearman's  $\rho = -0.18$  at  $p = 0.01$ . Additionally, the density of the trees correlates with the nearest forest area (for  $\sigma = 0$ , Spearman's  $\rho = 0.21$  at  $p = 0.003$ ). At the subregional level, there is a significant correlation with windbreak density in the immediate vicinity of a plot (Spearman's  $\rho = 0.20$  at  $p = 0.004$ ).

However, we failed to find a correlation with the hydrothermal index [54], which would have a biological meaning. We expected that the higher the hydrothermal index, the higher the density of trees in light forests. However, the hydrothermal index showed a negative tree density correlation (at the local level: Spearman's  $\rho = -0.23$  at  $p = 0.001$ , at the subregional level: Spearman's  $\rho = -0.36$  at  $p = 1.17 \times 10^{-7}$ , and at the regional level: Spearman's  $\rho = -0.89$  at  $p < 2.2 \times 10^{-16}$ ). In this case, we have a correlation in place, but obviously, there is no causation. Moreover, the hydrothermal index can well-correlate with the absolute height factor (Spearman's correlation coefficient  $\rho = 0.60$  at  $p < 2.2 \times 10^{-16}$ ). Thus, the climate effect is interrupted by the impact produced by the relief.

The anthropogenic load on pastures and hayfields tends to have an impact on the density of trees in light forests. The greater the proportion of unused natural forage lands, the higher the density of trees. For the local level: Spearman's  $\rho = 0.22$  at  $p = 0.002$ , at the subregional level: Spearman's  $\rho = 0.38$  at  $p = 3.05 \times 10^{-8}$ , and at the regional level: Spearman's  $\rho = 0.24$  at  $p = 0.001$ .

When comparing the tree density correlation with relief and nontopographic factors, we found that they are close values. In terms of their impact, the nontopographic factors can only exceed the relief at the local level. At the subregional and regional levels, they are weaker than the relief impact

(for tree seed import source location) or equal to the relief influence (as regards the anthropogenic load on pastures and hayfields).

#### 4. Conclusions

By the example of the Belgorod Region, for the first time for the landscapes of the forest-steppe uplands typical of the East European Plain, the main regularities of contemporary changes in the density of trees in light forests of the network of small dry valleys were revealed. The emergence of these light forests is the latest trend in the development of vegetation cover in the region.

The geographic features of these changes at various scale levels of the study (generalization) are very different. At the local level, a variegated spatial spreading is observed in which there are no obvious spatial patterns in changes in the tree density. More or less noticeable patterns begin to be determined with an increase in the generalization of tree density cartograms. At the subregional level, there is an alternation of areas with high and low densities of trees from the west to the east of the Belgorod Region. The areas of increased density mainly covered the middle and lower parts of the basins of the large rivers there, while the areas of low density of the trees in light forests at the subregional level are confined to the interfluves of the largest rivers of the region, as well as to the upper parts of their basins. The region-wide (that is, the most generalized) trend is a consistent increase in the density of light-forest trees in the small dry valleys network from the northwest to the southeast of this administrative region of SW European Russia.

Relief characteristics also affect the density of the trees in light forests growing in the small dry valleys network. Their influence is manifested through the differentiation of the moisture conditions in the territory studied and the creation of various conditions for the fixing of tree seedlings in the soil. At the local level, the relief influence is minimal, and the density of trees is largely due to other factors. Of all the relief characteristics at the local level, statistically significant correlation was found only for the slope and TRI. In general, at the subregional and regional levels of generalization, the closest correlation is observed with the absolute height of a particular territory. The second most important factor at the subregional level is the morphometric protection index, and at the regional level, it is the depth of small dry valleys.

The expansion of the light forests area into the small dry valleys network, which was observed in the country in the recent decades, is a very common phenomenon under modern changes in climate and land use/cover. This fact should be taken into account when planning the further economic use of the small dry valleys network as an inalienable element of the forest-steppe landscapes of the East European Plain while protecting its ecosystems, as well as for the development of recreational activities and ecological (environmental) tourism.

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