Determination of the shelterbelts influence on the average productivity of agrophytocenoses based on geostatistical analysis of spatial data and the NDVI

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Abstract. Shelterbelts effect positively on the elements of the microclimate, the water regime of soils, the agronomic properties of the soil, soil fertility in the agricultural landscape. The assessment of the influence of the density of shelterbelts on the overall productivity of arable land is poorly studied. In this study, the methodology for assessing of such impact with using GIS technologies is suggested. We propose to use the Normalized Vegetation Index (NDVI), as a standardized index showing the relative biomass of vegetation, averaged for each working area within the studied region for working plots of arable land with an area of more than 25 hectares in the Belgorod oblast. Paired correlation analysis between the density of shelterbelts and arable land productivity showed the weak relationship (R^2= 0.124), however, the classification of the density of shelterbelts with the interval of 0.5 km/km^2 allowed us to reveal the linear regression dependence y = 0.0059x + 0.5195 (R^2 = 0.989) of arable land productivity from the density of shelterbelts. Taking into account that many abiotic factors can affect the yield, we additionally proposed to carry out typing to identify areas of the same type in terms of the relief of the earth's surface, climatic conditions and productivity. To do this, the spatial clustering (K-means algorithm) was proposed to use. It was revealed that the productivity of agrophytocenoses increases by 10% with the increasing of the density of shelterbelts by 2 times with an average slope steepness of up to 2°. In physical terms, the yield of winter wheat will increase by 0.28 t/ha. Soil-protective crop rotations are an additional factor in increasing the value of the NDVI index on slopes more than 2°.

1 Introduction

Shelterbelts have a complex effect on the state of the agricultural landscape, positively: for arable land, they allow, in comparison with open areas of the field, to accumulate a snow mass by 1.2–1.8 times more, while the moisture supply of the territory increases by 1.2–2.7 times, the microclimate improves. The soil cover of the territory adjacent to the shelterbelts has an average density of 3.4–7.2%, and a specific gravity of 2.1–5.2% less than in the control

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areas. At the same time, the porosity of the soil increases by the average of 9.5–14.7%, and the humus content in it increases by 5.2–18.0%.

Thus, the increase of crop yields was revealed [1]. Shelterbelts protect soils from water and wind erosion; this reduces the removal of nutrients and biogenic substances. They increase the honey productivity of the agricultural landscape 2], act as the important nutritional factor for entomophages, and serve as a place of shelter for animals and birds [3]. In addition, shelterbelts reduce technogenic pollution.

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In the absence of care for shelterbelts, they can have a negative impact by increasing the number of insect pests and strengthening their harmfulness, in wet years they can lead to the development of fungal diseases [4], shading of crops, their root oppression are noted in the nearby territory.

In the above studies, the determination of the influence of shelterbelts on the ecological state of the agricultural landscape for individual plots was carried out. However, their different density within the agricultural landscape, the degree of framing of the site with shelterbelts may have a different little-studied effect.

Therefore, the aim of our study was to determine the influence of the density of shelterbelts on the productivity of arable land, taking into account climatic and geomorphological differences of the territory. At the same time, it became important to develop a method of using the remote sensing data and GIS technologies to identify the patterns of such impact.

2. Materials and methods

Previously, the manual vectorization based on DigitalGlobe satellite images of 2017 with the spatial resolution of 1 m and higher, located in the public domain and uploaded using ArcGIS Server, to create and analyze skeleton maps of the distribution of protective and anti-erosion shelterbelts was used [5]. The coordinate system of the WGS 1984 UTM Zone 37N projection was used in the study. The works were done in the ArcGIS 10.5 software package.

To build a map of the shelterbelts density, the "line density" tool with a search radius of 2.5 km equal to two average distances between shelterbelts was used.

To determine morphometric relief indicators (steepness and exposure of slopes), the digital evaluation model with a spatial resolution of 30 m was used, interpolated by the "Topo to raster" method according to land use maps M 1:25000.

Currently, there are a large number of variants of vegetation indices. They are selected experimentally (empirically) based on the known features of the spectral reflectivity of vegetation and soils [6]. The main advantage of vegetation indices is the ease of obtaining them and a wide range of tasks solved with their help. Thus, NDVI is often used as one of the tools for conducting more complex types of analysis and is the most reasonable in the literature [7].

The analysis of currently available satellite data shows [8] that the data of the MODIS spectroradiometer installed on NASA Terra and Aqua satellites is the most satisfactory for the organization of the assessment of production crops in some constituent entities of the Russian Federation. It is known that MODIS allows to obtain information in several spectral channels, on the basis of which vegetation indices can be calculated; at the same time, it is supposed [9] that the spatial resolution of the data (250 m) allows to get the information about the level of vegetation of individual fields in almost all agricultural regions of Russia.

To establish the NDVI index, medium spatial resolution images were selected (information products based on MODIS: MOD13Q1 (Vegetation Indices)). The use of this information product has shown significant opportunities in the analysis of seasonal changes in vegetation, identification of plowed fields, evaluation of projective coverage [10]. For the study, images for 2013-2017 were downloaded for the period April-October (the growing season), which allowed us to obtain average productivity values for crop rotations used in the Belgorod oblast [11]. On average, the five-field crop rotation is used. The images were processed in ENVI.

In the ArcGIS program, using the Raster Calculator, the sum of 35 NDVI rasters for the specified period was calculated. Since the specified images have an average spatial resolution (the cell size for the territory of the region is 330 m by 189 m), work areas with a size greater than 25 ha were additionally selected (the average size of work areas in the region is 58 ha), which made it possible to determine at least 4 pixels for each work area for analysis.

The matrix of working plots of arable land in the Belgorod oblast, vectorized by satellite images, has 25,238 plots, of which 16,586 plots have an area of over 25 hectares, 82.4% of all working plots are framed by shelterbelts to one degree or another.

At the first stage of the search for patterns of the influence of the density of shelterbelts on the productivity of arable land, the average values of NDVI, density of shelterbelts, HTC, exposure and slope steepness were established for the selected working areas using Zonal statistics tools. The resulting cloud of connections between NDVI and the density of did not allow to establish a close connection (R^2=0.124). However, when the data was reclassified by ranges, the strong correlation was established.

At the next stage, it was proposed to type the territory according to homogeneous indicators of the influence of the density of shelterbelts on the productivity of arable land, since it may depend on other natural factors.

At the present stage, more than 60 methods of spatial clustering have been proposed [12], but the K-algorithm of averages is most often used [13]. This clustering model is implemented in the ArcGIS 10.5 software package (the "Grouping Analysis" tool of the "Clustering Calculation" subset of the "Spatial Statistics" toolset). The input data was a vector layer of working areas with the entered parameters for each indicator (the average value of NDVI, the density of shelterbelts, the steepness of slopes, HTC). The input parameters for the tool are selecting experimentally by evaluating the output report. At the first stage of the tool's operation, the influence of variables on the formation of groups by the value of R^2 was analyzed (table 1). The higher it is, the greater the contribution of the variable.

Table 1. Estimation of the contribution of variables (R^2) to the grouping under different combinations.

Indicators	NDVI	Density of shelterbelts	Slope	HTC
NDVI, density of shelterbelts	0.52	0.60	-	-
NDVI, density of shelterbelts, slope steepness	0.67	0.73	0.71	-
NDVI, density of shelterbelts, slope steepness, HTC	0.40	0.50	0.33	0.55

The analysis of table 1 shows that when using 4 parameters (NDVI, density of shelterbelts, slope steepness, HTC), the contribution of each of them to the grouping is the lowest, and when using NDVI, density of shelterbelts slope steepness, the highest values of R^2 were obtained, therefore, for further analysis, this indicators were selected.

When setting parameters, spatial restrictions were not set for objects (this means that work sites do not necessarily have to be located side by side to get into the same group). When grouping, the calculation algorithm standardizes the values in the analysis fields, because variables with high variability have the greater impact on clustering than variables with less variability, which allows using different types of input data – coefficients, fractions, absolute indicators.

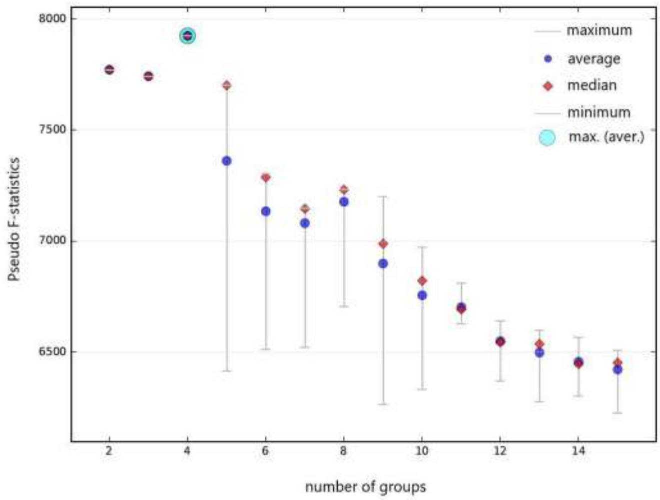

Fig. 1. Kalinsky-Kharabaz pseudo-F-statistics graph.

The optimal number of groups, which best allows classifying similarities and differences of objects, was measured using the Kalinsky-Kharabaz pseudo-F statistics, which also reflects the similarity of objects in a group and the difference between groups (figure 1). The maximum value of pseudo-F statistics indicates the optimal value of groups. As can be seen from figure 1, 4 groups are optimal for our study.

3. Results

According to the created skeleton maps of the shelterbelts distribution in the south of the Central Russian Upland (the territory of the Belgorod oblast), currently the average density of shelterbelts of all categories is 1.1 km/km^2 (table 2), and areas with the reduced density (less than 0.5 km/ sq.km.) are mainly confined to territories that are occupied by forests or settlements.

Table 2. Density of the shelterbelts within the Belgorod oblast.

Density of shelterbelts km/km^2	Square	
	km^2	%
0-0.5	3519.764	13.0
0.5-1.0	8932.995	32.9
1.0-1.5	9428.793	34.7
1.5-2.0	4335.974	16.0
2.0-2.5	875.5725	3.2
More 2.5	50.00202	0.2

Analysis of geospatial data on the steepness of the slopes showed that slopes with a steepness of 1-3° prevail in the region; they occupy 41% of the area (table 3).

Table 3. Distribution of the slopes of the Belgorod region by steepness, %.

Slope, °	Total by region	Arable land, %
0–1	23.0	19.6
1–3	41.0	54.2
3–5	18.8	18.5
5–10	14.7	7.8
>10	2.5	-

The western part of the region is flatter; in the east, there is a tendency of increasing steepness, which creates geomorphological prerequisites for the development of water erosion and siltation of rivers. The vast majority of arable land (76%) is located on slopes of more than 1°. The average steepness of the slopes of arable land is 2.35° ±1.07°.

The average NDVI values for the surveyed areas are 0.529±0.039.

In the eastern part the average NDVI values are lower than average, and in the western part they are higher. More than 1/5 of the arable land has an NDVI index value of more than 0.56.

The use of zonal statistics tools made it possible to determine the average NDVI value for the shelterbelts density raster reclassified according to the specified intervals (table 4).

Table 4. Dependence of arable land productivity (NDVI) on the density of forest strips.

Density of shelterbelts, km/ km^2	Average value of NDVI	Standard deviation for NDVI
0.0-0.5	0.532380	0.066748
0.5-1.0	0.522133	0.056827
1.0-1.5	0.525416	0.049834
1.5-2.0	0.528624	0.045947
2.0-2.5	0.531946	0.043520
More 2.5	0.533664	0.046423

The analysis of the table shows the productivity growth when increasing the density of the shelterbelts, starting with the density of 0.5 km/km^2. Such density is typical for upland territories, for which high productivity of crop rotation is typical. This gradation for determining the relationship was not used (figure 2).

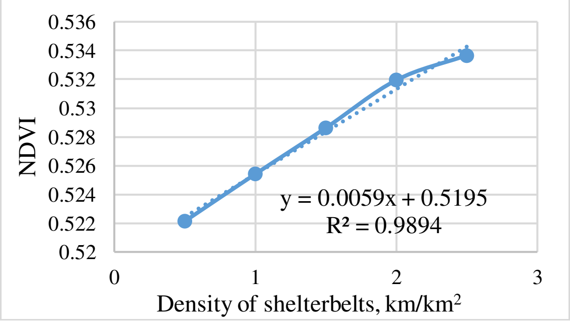

Fig. 2. Dependence of arable land productivity (NDVI) on the density of shelterbelts.

Figure 2 represents the direct strong relationship between the productivity of arable land (NDVI) and the density of the shelterbelts. However, visual analysis showed that the other parameters (in the west the index is higher than in the east of the region) other parameters may affect on the spatial variability of productivity (NDVI). Therefore, the hypothesis about the impact on productivity not only the density of shelterbelts, but also the steepness of slopes and HTC was put forward. Therefore, at the next stage, the territory differentiation according to these parameters was conducted (figure 3).

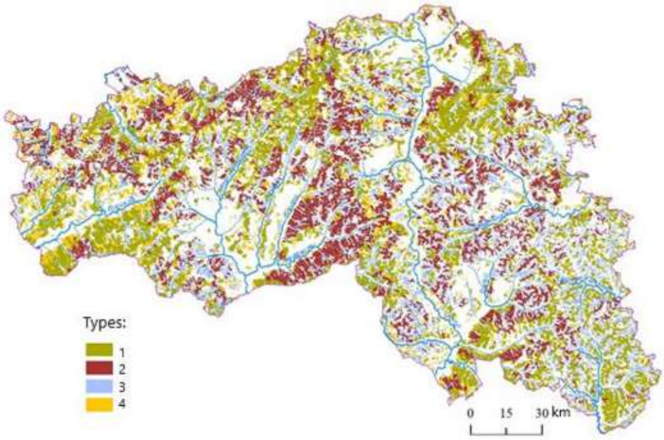

Fig. 3. Typification of the Belgorod region by the density of shelterbelts and indicators of arable land productivity (NDVI and slope steepness).

The analysis shows that in most of the territory (69.5% of the area of agricultural landscapes) on slopes with an average steepness of 1.8°, there is the direct relationship between the density of the shelterbelts and soil fertility (NDVI index), (types 1 and 2): with the growth of the shelterbelts density, the NDVI value increases and vice versa (table 5).

Table 5. Values of typing parameters for selected types.

Type	NDVI	Density of shelterbelts, km/ kм^2	Slope, degrees	Area of agricultural landscapes	
				kм^2	%
1	0.503±0.028	0.88±0.26	1.81±0.12	5161.3	38.4
2	0.527±0.026	1.61±0.028	1.80±0.08	4181.0	31.1
3	0.533±0.036	1.18±0.45	3.80±0.41	2476.5	18.4
4	0.585±0.032	0.93±0.35	1.93±0.49	1626.7	12.1

Type 3 is located on slopes with an average steepness above average (3.8°) and with a density of shelterbelts approximately equal to the average in the region, while the NDVI here turned out to be above average. These are territories classified as grain-grass and soil-protective crop rotations, in which the projective vegetation coverage due to greater saturation with grasses may be even higher than on slopes of lower steepness.

Type 4 differs by the NDVI value above the average by more than 10%, and the density of the shelterbelts is below average. This type includes the lower parts of slopes with soil-protective crop rotations saturated with perennial grasses, which causes high values of the vegetation index.

The revealed relationship between the yield of winter wheat grain and the vegetation index NDVI under conditions of sufficient moisture (HTC is 1.1–1.8) [14] allowed us to calculate that with a doubling of the density of the shelterbelts on slopes up to 2°, the increase in yield will be more than 10% or 2.8 hundredweight / ha.

4. Conclusion

The method for determining the dependence of arable land productivity (expressed in terms of NDVI) from the density of R^2 is suggested. The overlay operations with grids, as well as their reclassification were laid as a basis of it. Since the productivity of agrophytocenoses can also be influenced by other indicators (slope steepness, exposure, climatic parameters, etc.), it is proposed to additionally typify the territory according to these factors. To do this, it is possible to use automated methods of spatial clustering. The order of its application is given in the study.

The direct dependence of $y = 0.0059x + 0.5195$ ($R^2 = 0.9894$) of arable land productivity on the density of shelterbelts with an average steepness of 2° (69.5% of the total area of arable land plots of 25 hectares or more) has been determined. On slopes above 2°, the additional factor in increasing the value of the NDVI index is the use of crop rotations here. Therefore, additional research is needed to find the dependence not only on the density of shelterbelts, but also on the degree of framing of working areas with shelterbelts on slopes of different steepness in different climatic conditions. The conducted studies can help in determining the optimal density of shelterbelts to maintain the stable state of the agricultural landscape.

At the present stage the total length of shelterbelts on arable land is 29 thousand km, to ensure ecological balance, this length must be doubled. Thus, when carrying out effective agroforestry, the increase in yield in conversion to winter wheat grain within the arable land of the Belgorod oblast may amount to about 500 thousand tons.

Acknowledgments

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