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Assessing the Factors of Natural Afforestation on Postagrogenic Lands in the Forest-Steppe over the Last Decades

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Abstract

Analysis of tree vegetation recovery on abandoned agricultural lands is one of the key tasks in landscape research. This study considered the factors of forest cover of postagrogenic lands typical of the Central Russian forest-steppe. We applied a combination of geoinformation and statistical methods to analyze the relationship between climatic, geomorphological, and soil factors and the forest cover of abandoned agricultural lands. The results of this study showed varying strengths of the relationship between the climatic factors of the warm and cold seasons and the afforestation rate of postagrogenic lands. In the flat terrain region, warm-season climatic variables have a major effect on forest cover. Among the climatic factors, the precipitation of the warmest quarter and the hydrothermal coefficient show the strongest direct correlation with the forest cover of the abandoned agricultural lands. The accumulated temperature over the period with values above 10 °C and the average temperature of the warmest quarter show the strongest inverse correlation with forest cover. It has been established that soil type has a significant impact on the rate of abandoned lands afforestation. Forest cover on even-aged abandoned agricultural lands on gray forest soils (Haplic Phaeozems) is, on average, twice that of chernozem soils. The variation in forest cover is higher on abandoned croplands located on Chernozem. We analyzed forest cover as a variable dependent on various environmental conditions and proposed a number of multivariate regression models that estimate forest cover as a response to a combination of climatic, geomorphological, and soil conditions. As a result, the influence of various factors on the afforestation rate of postagrogenic lands was quantitatively shown.

Keywords: abandoned cropland; land resources; afforestation; environmental conditions; forest-steppe landscapes

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1. Introduction

At the beginning of the 21st century, abandoned agricultural lands became quite widespread in many natural zones of the Northern hemisphere [1–3]. The increase in abandoned agricultural land area is generally attributed to urbanization [4] and agricultural changes leading to greater efficiency and concentration on the most productive lands [5,6]. The decrease in arable land area has resulted in an increase in abandoned agricultural land [7,8]. Assessing the condition of postagrogenic lands is an urgent task, as their soil and plant resources can be reused [9,10]. The social and economic transformations over the past 30–40 years have led to a reassessment of the feasibility of low-profit agricultural land use in Russia. The consequence was the formation of postagrogenic lands on an area of 35–40 million hectares [11]. Another factor in recent decades is more intense climate change.

Researchers had to update the climate normals to track the global climate anomalies. In 2023, the World Meteorological Organization published the updated WMO Climatological Standard Normals for 1991–2020 to replace the 1981–2010 standard [12].

Abandoning agricultural lands leads to secondary succession [13–15]. Their consequence is the recovery of topsoil and vegetation cover [16–18]. For abandoned agricultural lands in forest and forest-steppe landscapes, afforestation is the typical form of secondary succession [19–21]. Natural afforestation increases the forest cover, affecting the biogeochemical cycles [22], microclimate [23,24], and hydrological properties [25]. Successions on abandoned agricultural lands, including those involving new tree vegetation, contribute to the restoration of soil properties [26–28] and help protect soils from erosion. Successions on abandoned agricultural lands are among the most important factors influencing the carbon cycle [29–32]. An analysis of fallow land restoration processes is necessary for planning their future use [33].

International studies in the field of agricultural land abandonment analysis can be divided into several areas. They are related to the development of strategies for their further use [34–36], involvement in climate change adaptation strategies [37,38], studying the carbon sequestration potential [39–41], analyzing forest cover restoration [42–44], studying ecosystem services [45,46], and modeling successions [47–49].

Postagrogenic successions, leading to the afforestation of abandoned agricultural lands, are the most common type of restoration of their vegetation cover in the context of the cessation of agricultural use. Assessing the processes of afforestation of abandoned agricultural lands has become a pressing issue for many regions of the world for several decades [50], including Europe [51,52]. In this regard, the analysis of afforestation of abandoned lands and restoration successions occupies a key place in research related to them. Identifying the characteristics of afforestation is associated with the solution of a number of problems related to their long-term use and the implementation of programs such as the Green Deal [53].

The analysis of afforestation of lands withdrawn from agricultural use, in turn, determines the need to study the factors that influence the formation of forest cover on postagrogenic lands. Such factors are mostly not known. This is due to the diversity of the planet's landscapes and conditions that can influence the afforestation of abandoned lands. Studying succession factors also requires determining the actual forest cover at a given stage of recovery following agricultural use. It is also necessary to quantify potential predictors of forest cover on abandoned lands. These primarily include climatic, geomorphologic, and soil properties. Each of these factors may be related to the rate of afforestation.

The study of factors influencing natural afforestation is particularly relevant in regions characterized by highly intensive agriculture. For these regions, we need objective data on the drivers of afforestation to make informed decisions in land use and natural resource management. One of such regions is the Central Russian forest-steppe on the East European Plain. The region features intense agriculture with mostly arable lands [54]. For example, in Belgorod Oblast (Central Chernozem Region), arable land accounts for more than half of the total land area [55,56]. Assessments of the afforestation on abandoned agricultural lands show that the region is characterized by high variations in forest cover due to different afforestation rates [57,58].

The purpose of this study is to analyze the factors influencing afforestation in abandoned agricultural lands of the Central Russian forest-steppe. The objectives of this study were: (1) to analyze the relationship between forest cover of abandoned croplands and various factors potentially influencing the regeneration of tree vegetation; and (2) to estimate forest cover of abandoned agricultural lands as a response to environmental factors.

2. Materials and Methods

2.1. Study Area and Research Methodology

The study area is located on the East European Plain in the forest-steppe zone within the Central Chernozem region. A significant portion of the region lies within the Central Russian Upland (Figure 1), with altitudes ranging from 80 to 300 m. Slopes are common in the region. Another characteristic feature is the fluvial network of small rivers [59], along with an extensive ravine system [60]. The total length of ravines in the southern part of the Central Russian Upland exceeds 10,000 km [61,62].

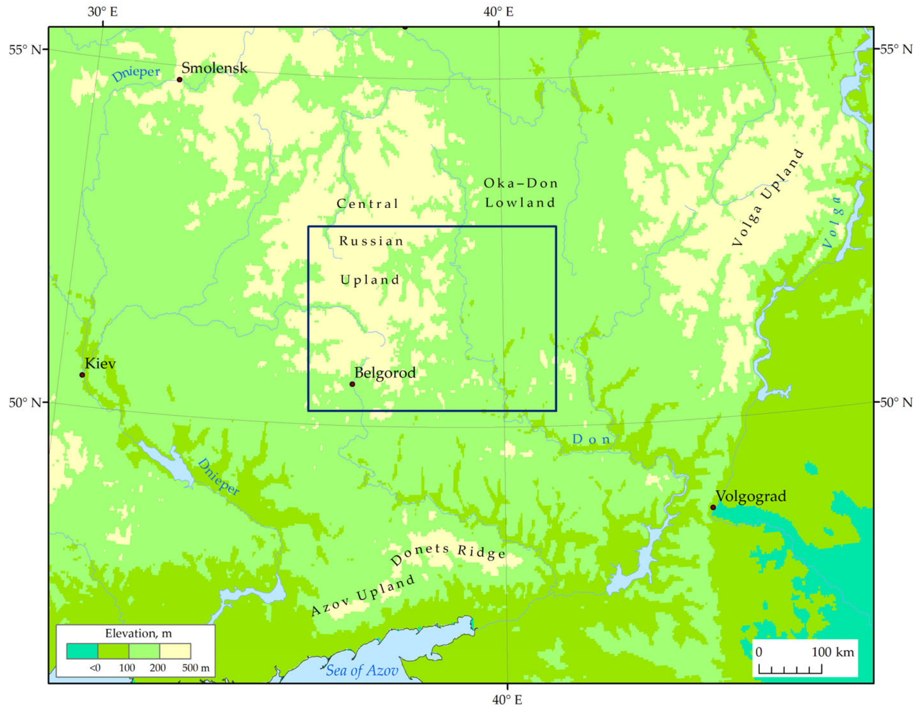

Figure 1. Study area.

The arable lands are on watersheds and slopes, predominantly separated by ravines and valleys. The region is in a temperate climate (Dfb according to the Köppen classification) [63]. The local annual mean and winter temperatures have been rising since the late 20th and early 21st centuries [64]. The spatial trends of climatic factors indicate variations from the northwest to the southeast [65]. The forest cover in the region is relatively sparse. The natural forest cover primarily consists of broadleaf forests dominated by oak [66]. The forest cover is highly fragmented, and small forest areas are common. Many of them are in the elevated areas of ravines and valleys. Relatively large forested areas are also present, predominantly located on the watersheds of the region's largest rivers. In addition to natural forests, a network of forest belts delineates the boundaries of cultivated lands. The forest belts are usually artificial. The region features chernozems and gray forest soils [67,68].

The abandoned agricultural lands of the Central Russian forest-steppe mostly feature deciduous tree species. These include apple, pear, elm, acacia, and birch. These tree species spread on sites adjacent to woodlands and forest belts, which are often located along the boundaries of both arable and abandoned agricultural lands. Variations in natural conditions and environmental factors within the region result in uneven forest cover on abandoned agricultural lands. It can vary from minimal values to almost 100% depending on the site conditions.

For this study, we collected data on the forest cover of abandoned agricultural lands with the identical period of secondary successions and a complex of environmental factors. These include terrain, climate, and soil characteristics. In this regard, a geoinformation approach was used, which made it possible to combine information on various characteristics of abandoned agricultural lands. The step-by-step methodological framework thus included a series of stages, from the formation of an analytical sample of objects to the construction of multivariate regression models (Figure 2). The first step of the experimental part of the study consisted of collecting the initial data. This involved preparing a sample of abandoned arable lands. At this stage, climatic, geomorphological, and soil characteristics were also collected. Continuous raster models were prepared for all of these characteristics.

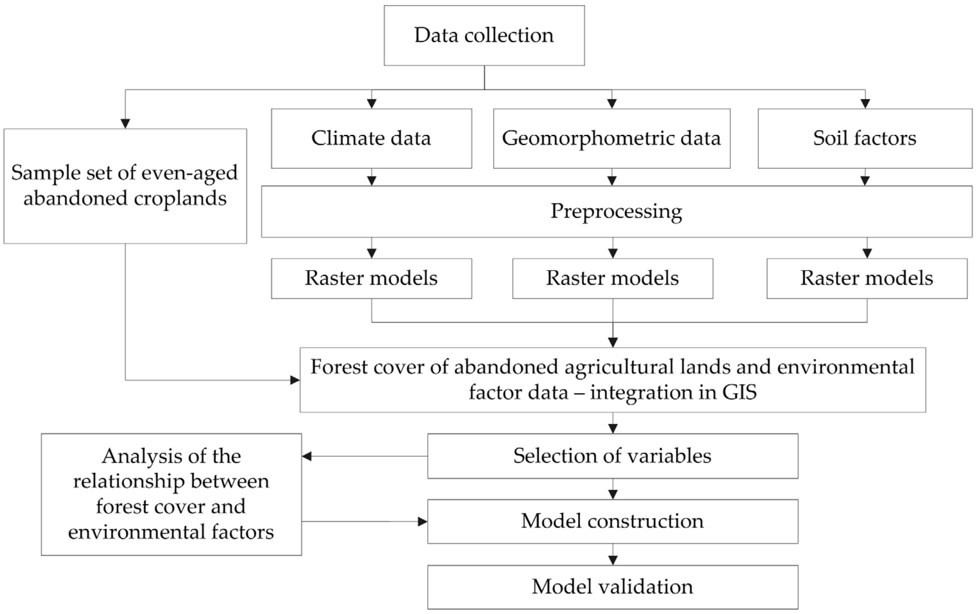

Figure 2. Flowchart of the study.

Based on these rasters, values of specific environmental factors were calculated for individual abandoned lands using geoinformation tools. This yielded the required dataset. It contained information on the forest cover of postagrogenic lands and the corresponding climatic, geomorphological, and soil characteristics. After combining the information on forest cover of postagrogenic lands and various environmental factors using geoinformation tools, a statistical analysis was performed. This analysis used the dataset obtained in the previous stage as input. The final stage consisted of statistical analysis of the data. At this step, the relationship between environmental factors and forest cover of abandoned agricultural lands was studied and multivariate regression models were calculated.

We studied abandoned land sites with ongoing natural afforestation. A group of criteria was used to select sites. First, the sample set needed to include abandoned agricultural lands showing a range of forest cover values from 0 to 1. Second, all abandoned croplands had to be even-aged; that is, their succession period needed to be identical, spanning two decades (2000–2020). Under the natural conditions of the Central Russian forest-steppe, forest vegetation can expand over a substantial part of a site within this period. Third, the sampled abandoned agricultural lands needed to represent areas with varying terrain slopes. Fourth, the lands needed to represent the main zonal soil types: chernozems and gray forest soils. Fifth, all study objects must be located in automorphic conditions, meaning they were not influenced by excessive moisture, floodplains, or wetlands.

We constructed the sample set through visual analysis of ultra-high spatial resolution mosaic images from open-access sources, primarily Google Earth, supplemented by Landsat

TM/OLI multispectral images [69]. We also used additional data. These included elevations derived from the global SRTM model and soil maps. To identify even-aged abandoned agricultural lands, we conducted a joint analysis of multi-temporal Landsat TM/OLI images acquired during the first two decades of the 21st century, along with ultra-high spatial resolution imagery from the end of the second decade. Landsat TM and subsequent satellite imagery (Landsat ETM+, OLI) are suitable for identifying abandoned lands based on specific characteristic features. The key indicator is the absence of plowing traces at various times during the vegetation season. Even-aged postagrogenic lands were selected by determining the year in which signs of plowing ceased on the lands. Analysis of multi-year image series confirmed the absence of signs of plowing in subsequent years. The location of objects in automorphic conditions was determined through a combined analysis of Landsat imagery and Google Earth imagery. Landsat TM/OLI imagery allows for the reliable detection of wetlands using the SWIR2–SWIR1–RED band synthesis. Abandoned croplands undergoing natural afforestation are also identified by the presence of continuous forest vegetation. Such vegetation is clearly visible on high and ultra-high spatial resolution images. We prepared a vector geoinformation layer and estimated the areas of all identified abandoned agricultural lands. The sample included 219 such sites (for example, refer to Figure 3).

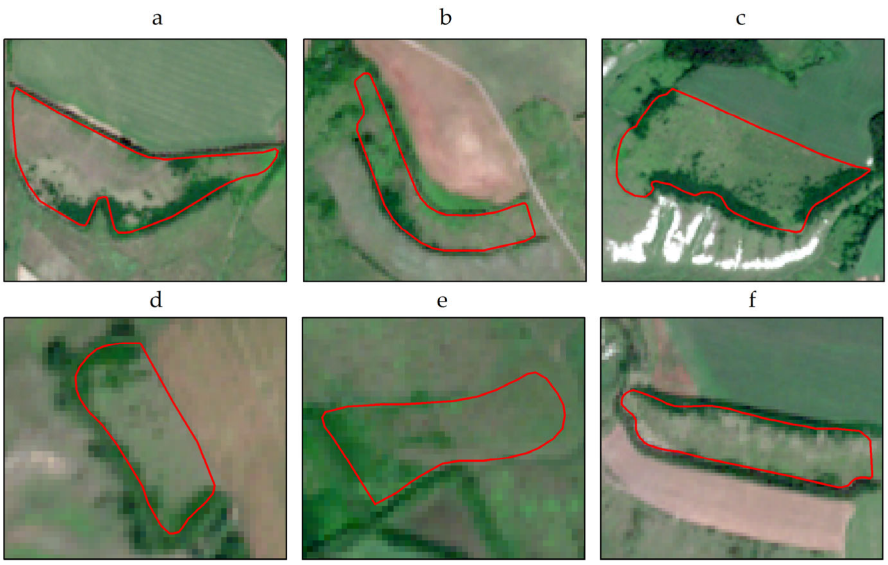

Figure 3. Examples of abandoned cropland in the south of the Central Russian Upland (**a**–**f**) in Sentinel-2 images. Synthesis of 4–3–2 bands.

In the subsequent preparatory stages, we estimated the forest cover of each site as of the end of the second decade of the 21st century, along with its geomorphological, soil, and climatic characteristics. These characteristics for each site were compiled in an attribute table associated with the vector layer delineating the boundaries of abandoned agricultural land sites.

2.2. Assessment of Afforestation on Abandoned Agricultural Lands

We measured actual forest cover values from high spatial resolution satellite imagery acquired in 2019–2020. Forest cover was calculated as the ratio of tree canopy area to the total area of each abandoned agricultural site. We visually assessed the afforestation of each site to estimate the area covered by tree vegetation. Ultra-high spatial resolution imagery, primarily from Google Earth, along with Sentinel-2 high spatial resolution imagery from 2019–2020, were used to estimate forest cover on abandoned agricultural lands. For each site of postagrogenic land, the forested portion was determined using visual image analysis.

The ratio of the resulting area to the area of the corresponding abandoned cropland plot determined its forest cover. The accuracy of the determination matched the detail of the satellite data used, meaning it was very high. Forest cover values were entered into the attribute table of the of abandoned agricultural land vector layer.

2.3. Estimating the Relationship Between Geomorphological Conditions and Forest Cover of Abandoned Agricultural Lands

The influence of geomorphological factors on the afforestation rate of abandoned croplands may manifest through the redistribution of solar radiation, heat, and moisture. Consequently, conditions may arise that either facilitate or hinder the growth of tree vegetation to different extents. To assess the influence of geomorphological conditions on the intensity of forest cover growth, we analyzed geomorphometric characteristics including surface absolute height, terrain slope, and slope exposure, expressed as the cosine of the exposure angle. We also calculated the Topographic Position Index [70] and Terrain Ruggedness Index [71]. The absolute height is measured in meters. The cosine of slope exposure (ranging from −1 to 1) indicates the degree of deviation from the northward direction. The topographic position index indicates the site location: above or below the middle of the slope. Positive values correspond to positions above the midpoint of the slope, while negative values correspond to positions below it. The terrain ruggedness index characterizes the height difference within the site. We used SRTM data to estimate geomorphometric characteristics. Then, we built raster models of them. After that, we applied zonal statistics to extract the properties for each site.

2.4. Assessment of the Relationship Between Climatic Factors and Forest Cover of Abandoned Agricultural Lands

Climatic characteristics are key factors influencing the recovery processes of tree vegetation on abandoned croplands. Our list of climatic variables accounts for the heat and moisture conditions as much as possible. The following climatic characteristics were used: annual average temperature; maximum temperature of the warmest month; minimum temperature of the coldest month; annual temperature range; average temperatures of the warmest and coldest quarters; annual precipitation; precipitation of the warmest quarter and precipitation of the coldest quarter; accumulated temperature over the period with values above 10 °C; precipitation of the period with temperatures above 10 °C; and the Selyaninov's hydrothermal coefficient. Temperatures above 10 °C are also known as active temperatures. We analyzed climatic characteristics using data from 13 weather stations located in or near the Central Chernozem Region of Russia. These are Bryansk, Rylsk, Bogoroditskoye-Fenino, Kamennaya Steppe, Pavelets, Kursk, Ponyri, Gotnya, Voronezh, Tambov, Valuiki, Rostashi, and Kalach weather stations. For the analysis, we used climatic characteristics values from each weather station, averaged over the succession period of the abandoned agricultural lands. The initial data were meteorological records from the period 2000–2020. Thus, the analysis was carried out using a period similar to the time of restoration successions on the studied postagrogenic agricultural lands.

All climatic characteristics were calculated from daily temperature and precipitation values [72]. Initially, we calculated values for each weather station for individual years within the 2000–2020 timeframe. Subsequently, the data were averaged over the entire period. In the next stage, we constructed raster models of the climatic variables to characterize their spatial distributions throughout the analyzed timeframe. The rasters were generated by interpolation using radial basis functions. We applied zonal statistics to extract climatic variable values for specific abandoned land sites. The raster models of climatic factors created in the previous step were used. In this way, the climatic characteristics were incorporated into the dataset to assess their relationship with forest cover on study objects.

2.5. Assessment of the Relationship Between Soil Conditions and Afforestation on Abandoned Agricultural Lands

Chernozems and gray forest soils (Chernozems (Haplic, Calcic, Luvic) and Haplic Phaeozems, according to WRB [73] respectively) are widespread in the Central Russian forest-steppe. In addition, within the framework of the state program of protective afforestation (1948–1953), sandy alluvial soils on pine forest terraces, which were only occasionally used for arable land, were used for pine plantations [74]. The ecological specificity of forests in forest-steppe and steppe environments is well diagnosed by differences in the rate of pedogenesis. Different soil types of the abandoned croplands may have contributed to different rates of afforestation. We estimated variations in afforestation rates by analyzing the actual forest cover of even-aged postagrogenic lands at the end of the second decade of the 21st century. We hypothesized that even-aged abandoned croplands with different soil types may show statistically significant differences in forest cover values. We used the *t*-test analysis to compare the lands forest cover. For the present study, the *t*-test to compare two independent samples was used. This is because the datasets of lands located on Chernozems and those on gray forest soils did not overlap. The significance level was 0.05.

2.6. Statistical Analysis of Abandoned Agricultural Lands Forest Cover Based on Complex of Environmental Factors

The analysis of the relationship between various environmental factors and forest cover of abandoned lands enabled a quantitative assessment of forest cover as a response to many environmental conditions. The assessment was performed using the multiple regression analysis method using the R (version 4.1.2). We considered forest cover as a dependent variable influenced by various predictors. These were climatic, geomorphological and soil characteristics. Among the many factors studied, only those variables that showed the highest statistically significant correlation with forest cover in earlier stages of research were selected for analysis. The significance level used was 0.05. All potential predictors of forest cover, except soil type, were quantified. Soil type (Chernozem or Gray forest soil) is a categorical variable. Therefore, its values were converted into a binary form: 0 or 1. We constructed regression models by selecting variables to maximize explanatory power while minimizing multicollinearity among predictors. Control of these parameters was necessary to ensure maximum efficiency of the model. Explanatory power was assessed based on the determination coefficient. The statistical significance was simultaneously assessed for each variable included in the regression model. We assessed multicollinearity among predictors in the regression models using the variance inflation factor (VIF). Many climatic factors may show strong intercorrelations while also showing strong correlations with forest cover of postagrogenic lands. In this regard, we considered several model configurations with different sets of predictors. The models included variables from different categories of environmental factors. We selected the models with the highest explanatory power. Thus, models were selected that explained the largest proportion of the variation in the dependent variable. For each regression model obtained, we analyzed the residuals, assessed their distributions, and the estimation of normality.

3. Results

3.1. Relationship Between Afforestation on Abandoned Agricultural Lands and Geomorphological Conditions

All geomorphometric factors, except for the cosine of exposure, showed a statistically significant relationship ($p < 0.05$) with forest cover of even-aged abandoned agricultural lands. Absolute height shows the strongest positive correlation with forest cover (Table 1).

Table 1. Parameters of the correlation between geomorphometric characteristics and forest cover of even-aged postagrogenic lands typical of the Central Russian forest-steppe.

Geomorphometric Factors	Spearman's Correlation Coefficient	Significance Level
Absolute height	0.43	0.000
Terrain slope	−0.26	0.000
The cosine of slope exposure	0.11	0.140
Topographic Position Index (TPI)	−0.20	0.005
Terrain Ruggedness Index (TRI)	−0.24	0.001

No statistically significant relationship was found between the cosine of exposure and forest cover of abandoned agricultural lands. The other geomorphometric factors show a negative relationship with lands forest cover. It should be noted that these relations are characteristic only for regional geomorphological conditions, i.e., for the conditions of an upland plain. For example, the increase in forest cover of abandoned lands with increasing absolute height is objective only for plain conditions, the altitudes of which in the region do not exceed 300 m.

Since terrain slope shows an inverse relationship with forest cover, these results suggest that the tree vegetation recovery rate is higher on flatter and higher-elevation abandoned agricultural lands. The topographic position index and terrain ruggedness index show little variation among the analyzed sites, as the entire region is essentially a hilly plain. For this reason, the influence of TPI and TRI on the lands forest cover is insignificant. Surface absolute height, indicating the location of lands at varying altitudes, shows the strongest relationship with forest cover. Therefore, this factor was included as a predictor in the multivariate regression analysis of forest cover of abandoned agricultural lands.

3.2. Relationship Between Abandoned Agricultural Lands Forest Cover and Climatic Factors

Forest cover of even-aged abandoned agricultural lands, estimated at the end of the second decade of the 21st century, shows the strongest positive and statistically significant relationships with the Selyaninov hydrothermal coefficient and precipitation of the warmest quarter (Figure 4). The warmest quarter lasts from July through September. The average temperature of the warmest quarter and the accumulated temperature over the period with values above 10 °C show the strongest inverse relationships with land forest cover. All correlation coefficients are statistically significant at the 0.05 level, except for those of the minimum temperature of the coldest month, precipitation of the coldest quarter, and average temperature of the coldest quarter.

A clear positive relationship exists between forest cover of postagrogenic lands and moisture availability during the warm season. Forest cover also shows a pronounced negative relationship with the thermal characteristics of the vegetation season. In this way, we identified climatic factors showing both strong and weak relationships with forest cover. The strong inverse relationship between forest cover and the average temperature of the warmest quarter serves as a preliminary indicator of the significant influence of temperature during the period of biological activity on the rate of natural afforestation on abandoned agricultural lands. The heat and moisture availability factors most strongly correlated with forest cover on abandoned croplands can be considered independent variables in the multivariate regression model.

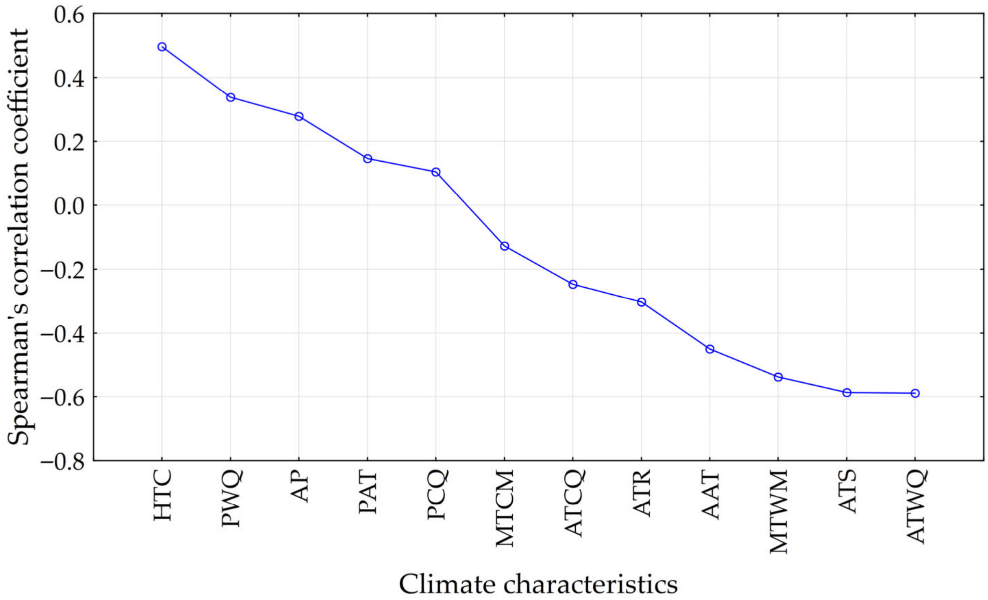

Figure 4. Spearman's correlation coefficients between forest cover of postagrogenic lands and climatic factors. HTC—hydrothermal coefficient, PWQ—precipitation of the warmest quarter, AP—annual precipitation, PAT—precipitation of the period with temperatures above 10 °C, PCQ—precipitation of the coldest quarter, MTCM—minimum temperature of the coldest month, ATCQ—average temperature of the coldest quarter, ATR—annual temperature range, AAT—annual average temperature, MTWM—maximum temperature of the warmest month, ATS—accumulated temperature over the period with values above 10 °C, ATWQ—average temperature of the warmest quarter.

3.3. Relationship Between Forest Cover of Abandoned Agricultural Lands and Soil Characteristics

The rate of natural afforestation on lands with gray forest soils is noticeably higher than on those with chernozem soils. Forest cover of even-aged abandoned lands located on gray forest soils is statistically significantly higher (at the 0.05 level) than that on Chernozems. These differences are quite significant (Table 2). For the same succession period, the afforestation rate of lands on gray forest soils is more than twice that of Chernozems.

Table 2. Forest cover parameters of even-aged postagrogenic lands of the Central Russian forest-steppe, located on different soil types.

Soil Type	Mean	Standard Deviation	Coefficient of Variation, %
Gray forest	0.54	0.30	55
Chernozem	0.26	0.25	96

Lands located on chernozem soils have a higher variation of forest cover compared to similar lands on gray forest soils. This may be largely attributed to the greater prevalence of Chernozem compared to gray forest soils in the Central Russian forest-steppe. Therefore, the variability of other factors influencing the rate of forest overgrowth is also greater for abandoned lands on chernozem soils. Chernozems, unlike gray forest soils, are present practically in all parts of the Central Russian forest-steppe with different climatic conditions. Gray forest soils are less common, particularly in the southern part of the region.

Soil type has a statistically significant effect on the afforestation rate of abandoned agricultural lands and can serve as a predictor. Statistically significant differences in forest cover of abandoned lands with different soil types indicate that soil conditions can be used as a categorical independent variable in forest cover modeling.

3.4. Forest Cover of Postagrogenic Lands as a Response to Environmental Factors

We analyzed the relationship between the forest cover of abandoned agricultural lands and different groups of environmental factors and obtained multiple regression models (Table 3). Each includes climatic, geomorphologic, and soil characteristics. The models have the same number of independent variables.

Table 3. Models of postagrogenic lands forest cover (F) based on various environmental factors.

No.	Model	R^2
1	F = 1.61 − 0.00063Tak + 0.0021H + 0.21ST	0.54
2	F = 0.49 − 0.12Tav + 0.0030H + 0.25ST	0.53
3	F = −0.7 + 0.28HTC + 0.0036H + 0.20ST	0.48
4	F = 4.31 − 0.17Tm + 0.0023H + 0.17ST	0.51

R^2—coefficient of determination, Tak—accumulated temperature over the period with values above 10 °C, Tm—maximum temperature of the warmest month, °C; Tav—annual average temperature, °C; HTC—hydrothermal coefficient; H—absolute height, m; ST—soil type: 0—chernozem soil, 1—gray forest soil.

Absolute height and soil type consistently show statistically significant contributions to the variation in forest cover of abandoned lands. Therefore, these factors were included in each regression model. Among the climate variables included in each model were temperature or moisture characteristics. As indicated by the determination coefficient (R^2), the explanatory power of the models is approximately identical, so the models are interchangeable.

All of the resulting regression models showed moderate explanatory power. This is due to the actual diversity of environmental factors, the influence of which cannot be fully accounted for in regression analysis. For example, factors such as land-use history, human management, and settlement patterns could have influenced the afforestation of abandoned croplands. However, using such factors to objectively assess their impact on the rate of afforestation is extremely difficult. The diversity of environmental factors and the difficulty of accounting for them are, therefore, the main limitations of the approach used and the resulting regression models.

The distribution of the model residual approximates normality, indicating that the models are free of systematic errors and provide a good fit to the data. In all cases (Table 4), the null hypothesis of normality cannot be rejected. The significance level from the Lilliefors test (a modified Kolmogorov–Smirnov test) significantly exceeds the 0.05 threshold.

Table 4. Results of assessing the normality of distribution of residuals for regression models based on the Lilliefors test (modified Kolmogorov–Smirnov test).

Model No.	Lilliefors (Kolmogorov–Smirnov) Statistic	Significance Level
1	0.058	0.22
2	0.056	0.26
3	0.047	0.55
4	0.065	0.10

The normality of distribution of the regression models residual is also indicated by the shape of the histograms (Figure 5). In all cases, it is bell-shaped.

Additionally, in all cases, residual with values closest to zero constitute the largest proportion. Values showing minimal deviation from the actual forest cover of abandoned agricultural lands predominate.

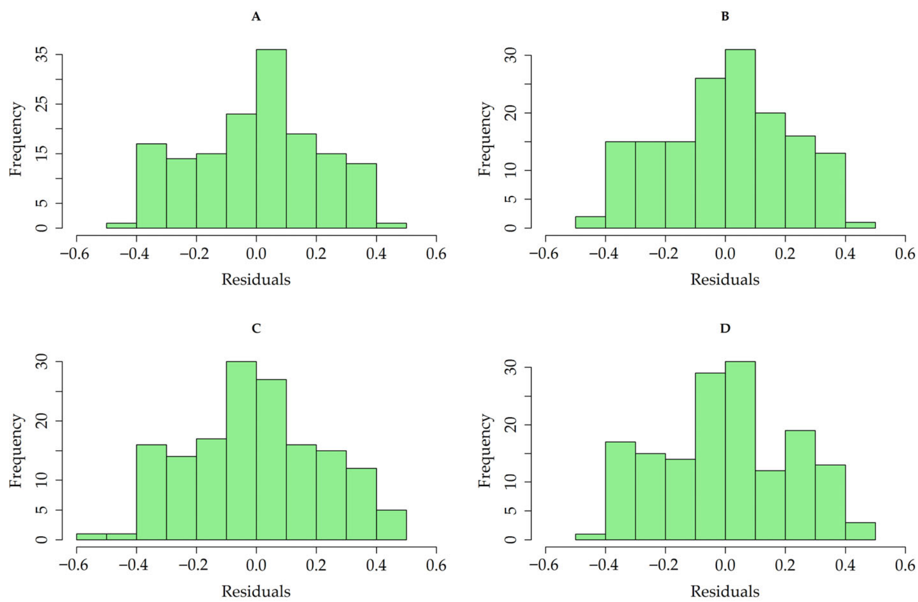

Figure 5. Histograms of residuals for models 1–4 (**A**–**D**). Explanations for model numbers are given in Table 3.

4. Discussion

Analysis of various environmental factors in the Central Russian forest-steppe revealed both strong and weak relations between climatic and geomorphological characteristics and forest cover of abandoned agricultural lands. Climatic factors show significant variation in both the strength and direction of their relationships with forest cover (Figure 4). There is a pronounced positive correlation between land forest cover and moist availability characteristics (precipitation of the warmest quarter, hydrothermal coefficient). There is also a negative correlation between forest cover and heat availability. These factors include the average temperature of the warmest quarter and accumulated temperature over the period with values above 10 °C. Therefore, heat and moisture availability variables can be grouped into two categories based on the direction of their relationship with forest cover of abandoned agricultural lands. We found no strong, statistically significant relationships between forest cover and climatic characteristics of the cold season. This may be due to the fact that the influence of climatic factors on forest cover is manifested only during the vegetation season. For example, winter precipitation accumulates soil moisture reserves, which tree vegetation primarily utilizes during the warm season.

Another characteristic of climatic factors is that variables related to heat and moisture availability show strong relationships with forest cover and are highly intercorrelated. For the heat availability category, such factors are accumulated temperature over the period with values above 10 °C, the maximum temperature of the warmest month, and the average temperature of the warmest quarter. Within the moisture availability category, the strongly correlated factors include precipitation of the warmest quarter, the hydrothermal coefficient, and precipitation of the period with temperatures above 10 °C. Due to intercorrelations among certain climatic characteristics, we analyzed them separately as predictors of afforestation on abandoned agricultural lands in multiple regression models. As the results show (Tables 3 and 4), each of the highly correlated variables can be used equally as a predictor.

Geomorphologic conditions influence the rate of afforestation, as higher elevation in relatively flat areas is associated with a higher afforestation rate. It should be noted that this conclusion applies only to flat terrains characteristic of the Central Russian forest-steppe, where absolute heights range from less than 100 to 350 m. This conclusion is supported by the strong positive relationship between forest cover of abandoned agricultural lands and absolute heights, alongside a negative relationship with terrain slope.

Significant differences in forest cover of even-aged abandoned croplands with different soil types (chernozems and gray forest soils) indicate a substantial influence of soil type on the natural afforestation rate. Given that the abandoned land sites were approximately the same age (20 years), the effect of different soil types on the afforestation rate in areas with closed tree vegetation is pronounced. Using the soil factor as a binary variable in the multiple regression models (Table 3) enhanced their explanatory power in all cases. There was no increase in the multicollinearity.

The obtained results showed that under certain combinations of environmental factors, the rate of afforestation of abandoned agricultural lands can be quite high. The forest cover values show (Table 2) that after a twenty-year period of restoration successions, forests can spread over a significant part of the land. These data are consistent with other assessments of afforestation of forest-steppe landscapes. For example, a high rate of forest cover formation was recorded for the ravine network of the region [27]. At the same time, the high variation in forest cover reflects its actual features, characteristic of abandoned agricultural lands in the Central Russian forest-steppe [57]. An assessment of the relationship between forest cover and environmental factors in the conditions of the region showed a significant role of the soil factor on the rate of afforestation of postagrogenic lands. Differences in forest cover of postagrogenic lands are also a consequence of the diversity of geomorphological conditions in the region. They are caused by the distribution of the ravine network, typical of the Central Russian Upland [61,62]. From the obtained regression dependencies, it is evident that the relief factor in the form of the absolute height of the terrain, as well as the soil factor, is included in each equation.

The results of the study can be used to make decisions about the use of postagrogenic lands, which requires taking into account various factors [9,11,35]. The main limitation of the approach used is the difficulty in accounting for the diversity of factors that can influence the forest cover of abandoned croplands. This is due to the fact that many afforestation factors are very difficult or impossible to account for when modeling the rate of forest cover formation.

5. Conclusions

This study revealed the relationship between climatic, geomorphological, and soil factors and the afforestation rate of postagrogenic lands located in the flat forest-steppe zone of the East European Plain. For the first time, a quantitative analysis of the complex factors influencing forest cover of abandoned agricultural lands has been conducted for the forest-steppe zone. Using the Central Russian forest-steppe as a case study, we identified terrain and climate characteristics showing varying strengths and directions of relationship with forest cover of even-aged abandoned agricultural lands. In the predominantly flat terrain characteristic of the study region, the relationship between forest cover of abandoned croplands and terrain features is expressed as an increase in forest cover with higher absolute heights and lower slope angles. In the Central Russian forest-steppe, the highest natural afforestation rates on abandoned agricultural lands occur on flat, elevated sites. The analysis of climatic factors revealed a positive relationship between forest cover and moisture availability during the warm season in this region. Heat availability factors show a negative relationship with forest cover of abandoned agricultural lands. We also analyzed differences in natural afforestation rates of abandoned lands across distinct zonal soil types: chernozems and gray forest soils. The forest cover of even-aged postagrogenic lands on gray forest soils is twice as high as its values for abandoned agricultural lands on chernozems.

The multivariate analysis of various environmental factors yielded a series of statistically significant multiple regression models treating forest cover of abandoned agricultural lands as a response to multiple variables. The regression models include climate, terrain, and soil characteristics. This study provides new insights into how environmental factors affect forest regeneration on abandoned croplands. The results can be applied to model forest cover of abandoned lands and to inform strategies for managing lands undergoing natural afforestation. Directions for further research should be related to the study of the relationship between various environmental factors and the afforestation rate on postagrogenic lands in other natural zones.

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