

Article

Economic Modeling of Shelterbelt Land Use on Agricultural Production in Ukraine

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Abstract

This study explores the impact of shelterbelt forest plantations on agricultural productivity in Ukraine. The purpose of this article is to investigate how forest belts and land use patterns affect crop yields and agricultural land use in Ukraine, and to compare these patterns with factors contributing to forest cover loss in EU countries in order to develop practical management recommendations. Using geoinformation modeling and correlation analysis, we examined the relationship between shelterbelt coverage and agricultural indicators, including land leasing, crop yields and the planted area under annual and biennial crops. The total area of agricultural land protected by these plantations amounted to 51.66 thousand hectares, generating an additional 206.64 thousand centners of grain annually. Given the average price of 12.23 euros per centner for cereals and legumes, the total economic effect was estimated at approximately 2.53 million euros per year. The study also presents theoretical and methodological approaches for mathematically modeling economic indicators of forestry land use, drawing on successful practices from the European Union regarding sustainable development under significant anthropogenic, economic, and climatic pressures. The results highlight that shelterbelt plantations, once established, are among the most cost-effective agronomic practices, offering long-term environmental and economic benefits for sustainable agricultural development.

Keywords: shelterbelts; agroforestry impact; forest cover loss; mathematical model; economic approach; spatial analysis



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1. Introduction

According to the World Bank, forests cover about a third of the earth's surface and are important for human life on the planet and the balanced development of the environment [1]. Forest cover and forests absorb and store most of the carbon dioxide, which

directly causes adverse climate change [2]. Forest areas regulate water cycles, maintain soil quality and reduces the risk of natural disasters, including floods. Many of these factors are underestimated, although they are the key to sustainable environmental and economic development of local, national and global economies [3]. Increasing funding for the conservation and protection of forests is a priority in the context of significant anthropogenic, economic and climatic load on natural systems. Although the rate of deforestation in some regions of the world has slowed somewhat, the world still loses about 14.5 million hectares of forest area per year [4–7]. According to Eurostat, the current European Union’s forestry land accounts for 5% of the world’s forest areas. Contrary to global trends of declining forestry land, the EU’s forest area is gradually increasing [8]. As of 2018, the total area of forests and other forestry land in the EU (European Union) reaches about 182 million hectares, of which 160.9 million hectares are under forests [8–12].

In the EU, forest and agricultural land, which prevents carbon emissions into the atmosphere, covers more than 75% of the territory. While deforestation or plowing generates emissions, measures to afforest or convert arable land into pasture can help absorb carbon. EU forests, according to the European Commission, annually absorb carbon emissions equivalent to almost 10% of Europe’s total greenhouse gas emissions. Land use and forestry, which include the use of soils, trees, plants, biomass and wood, directly contribute to the sustainable development of the environment [13–15].

The results of the economic indicators analysis of EU forestry as of 2019 show that the total production of forestry goods and services in actual prices amounted to 50.101 billion euros, gross value added in EU forestry (in actual prices)—25.836 billion euros, and the total forest area amounted to 160.9 million hectares. The total production of forestry goods and services is 311.38 euros/ha and gross value added 160.57 euros/ha per 1 ha of forestry land in the EU [16,17].

Recent scholarship positions forests and agroforestry as dual ecological–economic systems whose outcomes depend on policy, endowments, and management efficiency across countries. Global and EU policy frames emphasize forests’ roles in climate mitigation and land-based emissions management [18–20]. Comparative evidence from Ukraine’s Polissia and allied European settings shows how climate trends, water management, and reclamation shape land productivity and risk [21–24]. Methodologically, this body of work blends GIS inventories and monitoring [25–29] with econometric modeling of land value, degradation, and indirect land use [30–33], as well as multi-criteria optimization for hydrotechnical and polder systems [17,34–37]. Parallel research demonstrates that investment in water/irrigation and reclamation infrastructure has measurable ecological and economic returns, enabling comparisons of cost-effectiveness and resilience benefits [38–41]. Recent legal and policy studies further highlight how access regimes and land-use restrictions modulate these outcomes [42–44].

Within this broader field, shelterbelts and field windbreaks provide a comparative lens because they are deployed in Europe to East Asia. Cross-regional studies consistently find positive effects on yields and risk reduction, driven by wind reduction, soil-moisture conservation, and erosion control [45]. Reviews and bibliometric analyses also document carbon sequestration and alignment with bioeconomy goals [46–48]. Empirical work in Ukraine echoes these patterns: shelterbelts raise crop yields and adjacent land values, with effects mediated by farm structure and local conditions [49]. At the same time, current shocks—war-related damage to protective plantations and shifting precipitation regimes—underscore the need for region-specific adaptation strategies and offer a natural experiment for comparative evaluation across administrative units and countries [50].

The development of sustainable agricultural practices in Ukraine has become increasingly crucial due to the ongoing challenges of climate change, soil degradation, and the need for enhanced food security [51]. Among the various strategies aimed at improving agricultural productivity, the establishment of forest shelterbelts stands out as a particularly effective measure [52].

One of the most notable effects of forest shelterbelts is their ability to increase crop yields. Numerous studies have shown that shelterbelts can create a more favorable microclimate for crops by reducing wind velocity, which in turn decreases evaporation rates and protects crops from physical damage. For instance, research conducted by Ukrainian scientists such as V. M. Maliuha [28] and O. Sovakov [29] has demonstrated that the presence of forest shelterbelts can lead to a yield increase ranging from 5% to 25%, depending on the crop type, shelterbelt design, and local environmental conditions. These findings underscore the importance of integrating shelterbelts into the agricultural landscape as a means to boost productivity [53].

Also, based on the research of O. Sovakov—an increase in the yield of grain crops due to the influence of field protection forest plantations in the forest-steppe zone of the Right Bank of Ukraine, with an average rise of 4 centners per hectare. This increase is primarily attributed to the role of shelterbelt plantations in improving the microclimate of agricultural fields. Shelterbelts improve crop yields by reducing wind, retaining moisture, and preventing erosion [29]. By reducing wind erosion and preventing the loss of topsoil, shelterbelts contribute to the preservation of soil fertility, which is essential for the long-term productivity of agricultural lands. Furthermore, shelterbelts enhance biodiversity by providing habitats for various species, which can contribute to natural pest control and pollination services. The cumulative effect of these benefits leads to more resilient agricultural systems that are better equipped to withstand the impacts of climate change and other environmental stresses [54].

In Ukraine, a comprehensive agricultural development plan was previously absent [55]. This void underscores the need for a strategic framework for the agricultural and forestry sectors, particularly in countries with strong potential for transformation amid European integration [36]. The restructuring of Ukraine's economy further demands a targeted approach to agricultural production and development [37]. To address these challenges, a national program should be established to implement diverse methods across Ukraine's agricultural regions. The article seeks to fill this gap by proposing new strategies for sustainable growth in these vital areas. Therefore, the goals of this research were as follows:

- (1) To quantify the impact of forest shelterbelts on agricultural production in Ukraine, with a specific focus on their effect on crop yield using correlation analysis to assess the relationship between the area of shelterbelts and agricultural output;
- (2) To develop a methodology for creating mathematical models of economic indicators for the rational use of forestry land, drawing on best practices from the European Union for use in other countries;
- (3) To evaluate the forestry rent generated by these plantations, which could provide a financial incentive for their establishment and maintenance;
- (4) To visualize the impact of shelterbelts across different landscapes by employing geoinformation modeling.

2. Materials and Methods

2.1. Database

We used two datasets: (1) EU countries to study forest cover loss, and (2) Ukrainian regions/communities to study shelterbelts and agriculture. We kept only records with all key numbers available and in the same units (thousand hectares, million euros, thousand people). First, we checked the data for obvious errors and unusual values. We then measured simple links between variables using Pearson correlations. For the main results, we ran ordinary least squares regressions and reported how well each model fits (R^2), whether it is statistically meaningful (F test), and whether the residuals look DW (Durbin–Watson). To avoid misleading results, we also checked that the explanatory variables were not too closely related to each other and re-ran the models after trimming extreme values; the main patterns did not change. To compare regions by overall similarity, we standardized indicators and built a Neighbor-Joining (NJ) tree. GIS data on shelterbelts were used to calculate protected areas and to turn yield effects into an estimate of extra production.

This study employed a combination of statistical analysis and geoinformation modeling to examine the impact of forest shelterbelts on agricultural production in Ukraine as of 2023. It began with a detailed correlation analysis aimed at evaluating how the area of shelterbelt plantations influenced key agricultural indicators. The primary variables analyzed included the total area of land leased under contracts, which reflected the overall level of agricultural activity and provided a baseline for identifying changes in land use patterns. The yield of agricultural crops, specifically wheat, peas, and barley, was examined to determine the extent to which shelterbelts contributed to crop productivity. The planted area under annual and biennial crops was also assessed to identify shifts in crop diversity and land allocation associated with the presence of shelterbelts.

2.2. Mathematical Modeling

To develop the appropriate linear econometric equations, it should be borne in mind that in economics the value of the performance indicator is determined by the influence of a number of factors, each of which in some way affects the performance indicator. Because of this, in the process of studying the joint influence of a number of independent indicators—factors x on the studied performance indicator y , multiple correlation models were calculated [38]. At the same time, in multiple correlation models, the dependent variable y is considered as a function of several independent variables x_j (Formula (1)) [20,31,39–41]:

$$y = f(x_1, \dots, x_j, \dots, x_m) + u, \quad (1)$$

In case of a linear relationship of each factor with the dependent indicator, the linear equation of multiple correlation is used, which for m factors has the following form (Formula (2)) [42]:

$$y = a_0 + a_1x_1 + a_2x_2 + \dots + a_jx_j + \dots + a_mx_m = a_0 + \sum_{j=1}^m a_jx_j + u, \quad (2)$$

The coefficients of the multiple regression equation on a natural scale are determined using the least squares method by solving a system of normal equations (system of Formula (3)) [38,43]:

$$\begin{aligned}
& na_0 + a_1 \sum_{i=1}^n x_{1_i} + a_2 \sum_{i=1}^n x_{2_i} + a_3 \sum_{i=1}^n x_{3_i} + \dots + a_j \sum_{i=1}^n x_{j_i} + \dots + a_m \sum_{i=1}^n x_{m_i} = \sum_{i=1}^n y_i \\
& a_0 \sum_{i=1}^n x_{1_i} + a_1 \sum_{i=1}^n x_{1_i}^2 + a_2 \sum_{i=1}^n x_{2_i} x_{1_i} + a_3 \sum_{i=1}^n x_{3_i} x_{1_i} + \dots + a_j \sum_{i=1}^n x_{j_i} x_{1_i} + \dots + a_m \sum_{i=1}^n x_{m_i} x_{1_i} \\
& \quad = \sum_{i=1}^n y_i x_{1_i} \\
& a_0 \sum_{i=1}^n x_{2_i} + a_1 \sum_{i=1}^n x_{1_i} x_{2_i} + a_2 \sum_{i=1}^n x_{2_i}^2 + a_3 \sum_{i=1}^n x_{3_i} x_{2_i} + \dots + a_j \sum_{i=1}^n x_{j_i} x_{2_i} + \dots + a_m \sum_{i=1}^n x_{m_i} x_{2_i} \\
& \quad = \sum_{i=1}^n y_i x_{2_i} \\
& a_0 \sum_{i=1}^n x_{3_i} + a_1 \sum_{i=1}^n x_{1_i} x_{3_i} + a_2 \sum_{i=1}^n x_{2_i} x_{3_i} + a_3 \sum_{i=1}^n x_{3_i}^2 + \dots + a_j \sum_{i=1}^n x_{j_i} x_{3_i} + \dots + a_m \sum_{i=1}^n x_{m_i} x_{3_i} \\
& \quad = \sum_{i=1}^n y_i x_{3_i} \\
& a_0 \sum_{i=1}^n x_{j_i} + a_1 \sum_{i=1}^n x_{1_i} x_{j_i} + a_2 \sum_{i=1}^n x_{2_i} x_{j_i} + a_3 \sum_{i=1}^n x_{3_i} x_{j_i} + \dots + a_j \sum_{i=1}^n x_{j_i}^2 + \dots + a_m \sum_{i=1}^n x_{m_i} x_{j_i} \\
& \quad = \sum_{i=1}^n y_i x_{j_i} \\
& a_0 \sum_{i=1}^n x_{m_i} + a_1 \sum_{i=1}^n x_{1_i} x_{m_i} + a_2 \sum_{i=1}^n x_{2_i} x_{m_i} + a_3 \sum_{i=1}^n x_{3_i} x_{m_i} + \dots + a_j \sum_{i=1}^n x_{j_i} x_{m_i} + \dots \\
& \quad + a_m \sum_{i=1}^n x_{m_i}^2 = \sum_{i=1}^n y_i x_{m_i}
\end{aligned} \tag{3}$$

The bond density in multiple correlations characterizes the total correlation coefficient R , which is calculated through the residual σ_u and total variance σ_y by the Formula (4) [38,43]:

$$R = \sqrt{1 - \frac{\sigma_u^2}{\sigma_y^2}}, \tag{4}$$

Reliability R (model adequacy) is determined by Fisher's F -criterion, the value of which must be not less than the tabular value (Formula (5)) [4,38]. All F criteria calculated during the study, exceed the tabular value, which is evidence of the adequacy of the equations [43].

$$F_p = \frac{R^2(n - m - 1)}{(1 - R^2)m}, \tag{5}$$

The value of R^2 , which is the coefficient of determination, demonstrates what part of the variance is explained by the variation in the linear combination of arguments having the corresponding values of the regression coefficients a_j [38]. The Darbin-Watson (DW) criterion, which is used to detect autocorrelation of first-order remainders of the regression model [30,44], is also calculated Equation (6):

$$DW = \frac{\sum_{t=2}^n (\epsilon_t - \epsilon_{t-1})^2}{\sum_{t=2}^n \epsilon_t^2}, \tag{6}$$

Based on the comparison of the obtained results of DW with the tabular values it can be stated that in all developed models autocorrelation is practically absent.

The next stage of the study involved establishing a correlation between the area of lost forest cover in the EU (according to Forest Global Watch) [8,45], as a resultant factor (Y) and the following factors:

- population, million people (X_1);
- area of the EU member state, thousand km² (X_2);

- area of forestry land, thousand hectares (X_3);
- ownership of forestry land (private (X_4), state (X_5));
- forest area suitable for commodity production, thousand hectares (X_6);
- total production of forestry goods and services at actual prices, million euros (X_7);
- gross value added at basic prices, million euros (X_8);
- gross growth of fixed capital in forestry, million euros (X_9);
- number of employees in forestry, thousand people (X_{10});
- relative indicators: (1) number of employees in forestry per 1 ha of forest area suitable for commodity production (X_{11}); (2) labor productivity indicators (volume of felled trees, thousand m^3 /number of employees) (X_{12}), (gross value added, thousand euros/number of employees (X_{13})).

2.3. Statistical Analysis

The correlation analysis employed statistical software to compute correlation coefficients between the area of forest shelterbelts and each of the selected agricultural indicators. Pearson’s correlation coefficient were used to measure the strength and direction of these relationships Equation (7) [46].

$$R_{xy} = \frac{\sum_{i=0}^{n-1} (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=0}^{n-1} (x_i - \bar{x})^2 \sum_{i=0}^{n-1} (y_i - \bar{y})^2}} \tag{7}$$

This analysis could help to quantify the extent to which forest shelterbelts contribute to variations in crop yields, land leasing patterns, and planting decisions, laying the groundwork for more detailed spatial analyses in the subsequent stages of the study (Table 1. The analysis was focus on identifying statistically significant relationships between the area of forest shelterbelts and changes in these agricultural indicators, providing insight into how shelterbelt size and distribution influence agricultural productivity. The multiple linear regression analysis was conducted to examine the relationship between various agricultural factors and an outcome variable. The dataset included administrative regions of Ukraine and agricultural metrics such as forest shelterbelt areas, leased agricultural land, crop yields (wheat, peas, and barley), and planted and harvested areas of different types of farms.

Table 1. Matrix of paired correlation coefficients of indicators, which characterize the loss of forest cover in the EU.

	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	X_{11}	X_{12}	X_{13}
Y	0.09	0.62	0.89	−0.36	0.36	0.85	0.53	0.8	0.91	0.47	−0.37	0.52	0.71
X_1		0.73	0.41	−0.18	0.18	0.47	0.64	0.51	0.3	0.62	−0.13	0.04	0.26
X_2			0.88	−0.27	0.27	0.9	0.75	0.82	0.71	0.72	−0.34	0.29	0.59
X_3				−0.31	0.31	0.99	0.68	0.88	0.91	0.65	−0.41	0.43	0.7
X_4					−1	−0.31	−0.13	−0.29	−0.44	0.03	0.24	−0.38	−0.55
X_5						0.31	0.13	0.29	0.44	−0.03	−0.24	0.38	0.55
X_6							0.74	0.9	0.87	0.65	−0.53	0.43	0.73
X_7								0.92	0.65	0.76	−0.26	0.37	0.65
X_8									0.86	0.73	−0.38	0.46	0.79
X_9										0.61	−0.44	0.64	0.66
X_{10}											0.12	0.05	0.31
X_{11}												−0.34	−0.27
X_{12}													0.66

Neighbor-Joining (NJ) clustering is a hierarchical method used to construct phylogenetic trees or analyze regional similarities in datasets. The Gower distance method was

used to calculate distances and examine the administrative areas of Ukraine. The analysis was performed using Past version 4.17.

2.4. Study Area

Detailed research the study of the positive agroforestry impact of forest shelterbelts in Ukraine was conducted in Vasylykiv district, located on the left bank of the Forest-Steppe natural and climatic zone of the Kyiv region (Figure 1). This area was selected as a model due to its diverse agricultural activities and the presence of numerous shelterbelt plantations. The research covered 43 rural communities, providing a comprehensive overview of how shelterbelts influence local agricultural production.



Figure 1. Location map of study area.

2.5. Geoinformation Modeling

Following the correlation analysis, the study proceeded to geoinformation modeling, which involved using Geographic Information System (GIS) software ArcGIS Pro 3.2 to

spatially analyze the impact of forest shelterbelts on agricultural landscapes. The second phase of the research focused on visualizing the spatial distribution of forest shelterbelts and their potential influence on agricultural production. GIS software was used to create digital maps showing shelterbelt locations, patterns of agricultural land use, and other relevant environmental factors. By incorporating data on the documented positive agroforestry impacts of shelterbelts, the GIS model enabled the estimation of their area of influence. This approach provided valuable insights into the potential benefits of shelterbelts across various agricultural landscapes in Ukraine. The GIS-based modeling accounted for a wide range of agroforestry effects associated with shelterbelts, as reported in existing research [29].

To accurately assess the impact, topographic maps at a scale of 1:10,000 were used for geographic information modeling (GIS), which allowed precise mapping of the shelterbelt locations and their spatial influence on adjacent agricultural fields. In the GIS modeling, buffer zones representing the effective range of shelterbelt impacts were established. These zones were classified according to the height (H) of the forest plantations. For example, the closest buffer, up to 1H (up to 25 m), represents areas where the shelterbelts have the most direct influence, offering strong protection against wind and erosion. Buffer zones from 1–15H (25–375 m) and 15–30H (375–750 m) show a diminishing but still notable effect, while areas beyond 30H (over 750 m) are considered open fields without significant shelterbelt protection (Figures 2 and 3). In the Figure 3: red colour—zone of influence: up to 1H from the forest belt (up to 25 m); pink colour—zone of moderate influence: from 1H to 10H (25–250 m); light pink colour—zone of weak impact: from 10H to 15H (250–375 m).

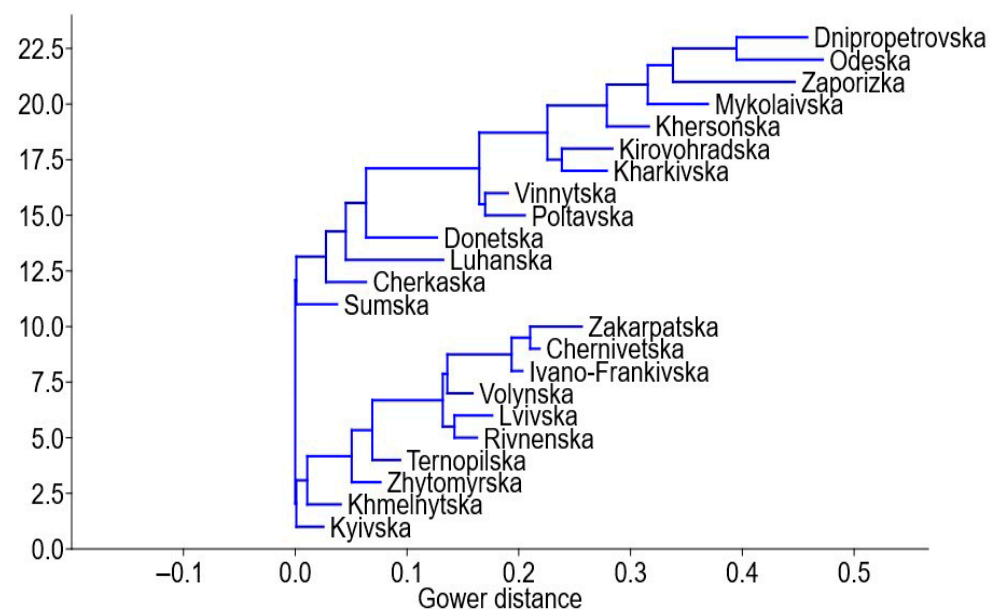


Figure 2. Neighbor-Joining (NJ) clustering for administrative areas of Ukraine.

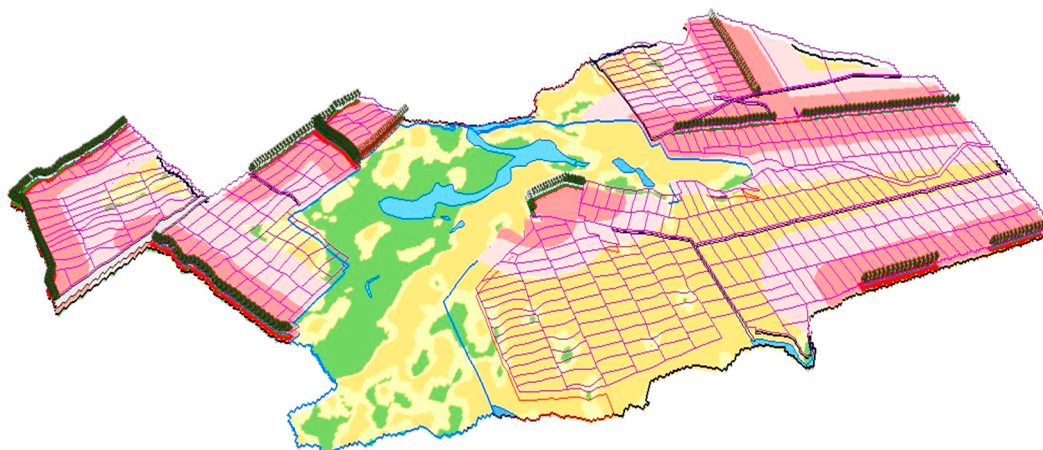


Figure 3. Geoinformation modeling of the positive impact of shelterbelt forest plantations on adjacent agricultural land in one of the rural community in Vasylkiv district of the Kyiv region in Ukraine. Source: own calculations based on [29,30].

3. Results

As a result of correlation analysis, correlation coefficients were obtained, which characterize the relationship of the resulting factor (Y) with the corresponding indicators (X_1 – X_{13}). The correlation analysis showed a strong positive relationship between shelterbelt area and agricultural indicators. A coefficient of 0.73 indicated that regions with more shelterbelts had more leased farmland. Crop yields were also positively affected, with correlations of 0.78 for wheat, 0.80 for peas, and 0.73 for barley, suggesting enhanced productivity. The strongest correlation, 0.87, was observed between shelterbelt area and the planted area under annual and biennial crops, highlighting their influence on land use decisions. These associations align with established windbreak mechanisms: reduced wind speed lowers evapotranspiration and lodging risk, while snow and residue retention improve soil moisture and nutrient cycling. The stronger link with annual/biennial crops suggests risk mitigation is a key channel—shelterbelts appear to shift planting decisions toward more intensive rotations. Still, correlation does not imply causation, part of the pattern may reflect joint determinants such as better-capitalized farms or local governance quality. This motivates multivariate checks and, ideally, panel or instrumental strategies in future work (Table 1).

Table 2 outlines a set of performance and factor indicators used to analyze forest cover loss in EU countries, with the main dependent variable being the area of forest cover loss (y), measured in thousand hectares. Factor indicators include geographic, economic, and labor-related metrics such as country area, forestry land area, forest suitability for commodity production, total forestry output, gross value added, capital investment, and labor productivity. These indicators are presented in consistent units—thousand hectares, million euros, and thousand people—allowing for comparative analysis across countries and helping to identify potential drivers of forest loss. Conceptually, endowment variables (area, forestry land, commodity-suitable forest) capture exposure, while economic and labor variables capture pressure and efficiency. Because output growth can arise from either extensive expansion or productivity gains, coefficient signs are a priori ambiguous and must be learned from the data.

Table 2. Indicators characterizing the use of forest resources.

Performance Indicators			Factor Indicators		
Name	Units of Measurement	Symbol	Name	Units of Measurement	Symbol
Area of forest cover loss in EU countries	thousand hectares	Y	Country area	thousand km ²	X ₂
			Area of forestry land	thousand hectares	X ₃
			Area of suitable forests for commodity production	thousand hectares	X ₆
			Total production of forestry goods and services at actual prices	million euros	X ₇
			Gross value added at basic prices	million euros	X ₈
			Gross fixed capital growth in forestry	million euros	X ₉
			Volume of felled trees, thousand m ³ /number of employees	thousand m ³ /thousand people	X ₁₂
Area of forests suitable for commodity production in EU countries	thousand hectares	X ₆	Gross value added, thousand euros/number of employees	m ³ /thousand people	X ₁₃
			Area of forest cover loss in EU countries	thousand hectares	Y
			Total production of forestry goods and services (at actual prices)	million euros	X ₇
			Gross value added at basic prices	million euros	X ₈
			Gross fixed capital growth in forestry	million euros	X ₉
Total production of forestry goods and services at actual prices in EU countries	million euros	X ₇	Number of employees in forestry	thousand people	X ₁₀
			Gross value added, thousand euros/number of employees	thousand euros/thousand people	X ₁₃
			Area of forest cover loss in EU countries	thousand hectares	Y
			Gross value added at basic prices	million euros	X ₈
Gross value added at basic prices	million euros	X ₈	Gross fixed capital growth in forestry	million euros	X ₉
			Number of employees in forestry	thousand people	X ₁₀
			Gross value added, thousand euros/number of employees	thousand euros/thousand people	X ₁₃
			Area of forest cover loss in EU countries	thousand hectares	Y

The regression modeling results revealed several key indicators related to forest cover loss in EU countries (Table 3). The model for forest cover loss (Y) demonstrated a Durbin-Watson value of 1.711, a high coefficient of determination (R^2) of 0.949, and Fisher's F-criterion of 50.55, indicating a strong fit. The area of forests suitable for commodity production (Y_6) showed values of 1.751 for DW, 0.883 for R^2 , and 31.92 for F. Total production of forestry goods and services (Y_7) yielded 1.651, 0.961, and 136.958, respectively, marking it as one of the most statistically significant models. Gross value added in the forest sector (Y_8) had a DW of 1.896, R^2 of 0.632, and F of 43.023. Additional indicators included gross fixed capital growth in forestry with DW = 1.782, R^2 = 0.845, and F = 28.47, and the number of employees in forestry with DW = 1.724, R^2 = 0.798, and F = 22.61. Taken together, the metrics imply two regimes: endowment-driven pressure where large commercially suitable stocks coincide with higher potential loss, and scale-driven pressure where total output tracks loss unless offset by efficiency. The moderate fit for value added hints at partial decoupling—countries earning more per unit harvest may reduce loss at a given output.

Policy thus favors efficiency-oriented growth (raising value added per worker and per unit capital) and targeted stewardship in high-endowment contexts rather than uniform caps.

Table 3. Performance indicators that characterize the use of forestry land in the EU.

Modeling Indicator	Regression Equation	Darbin-Watson Criterion (DW)	Coefficient of Determination	Fisher's F-Criterion
Area of forest cover loss in EU countries ($Y \rightarrow X$ in subsequent regressions)	$Y = 20,023 - 2.247 \times X_2 + 0.159 \times X_3 - 0.086 \times X_6 - 0.232 \times X_7 + 0.770 \times X_8 + 120.584 \times X_{12} - 0.583 \times X_{13}$	1.711	0.949	50.55
Area of forests suitable for commodity production in EU countries ($X_6 \rightarrow$ for the equation we take the symbol Y_6)	$Y_6 = 775.179 + 0.318 \times X - 1.722 \times X_7 + 7.085 \times X_8 + 35.409 \times X_{10} - 4.322 \times X_{13}$	1.751	0.883	31.92
Total production of forestry goods and services at actual prices in EU countries ($X_7 \rightarrow$ for the equation we take the symbol Y_7)	$Y_7 = 346.572 - 1.303 \times X + 2.669 \times X_8 - 0.734 \times X_{10} - 6.616 \times X_{13}$	1.651	0.961	136.958
Gross value added (in actual prices) in the forest sector of the EU economy ($X_8 \rightarrow$ for the equation we take the symbol Y_8)	$Y_8 = 366.373 + 1.055 \times X$	1.896	0.632	43.023

The analysis of forest cover loss in EU countries provides a broader context for understanding the Ukrainian reality. It demonstrates how the intensity of forest resource use and economic development affect the state of forests at the macro level. The Ukrainian part of the study deepens this vision by showing practical mechanisms for forest conservation and restoration through a system of protective forest belts. This transition allows for a smooth combination of European trends with local examples of rational land use, creating a coherent research logic.

The regression analysis yielded a range of coefficients and statistical measures across agricultural indicators (Table 4). The constant term was estimated at 9.321 with a standard error of 45.035, resulting in a t-value of 0.20697 and a p -value of 0.83901, indicating no statistical significance. Among the independent variables, the total area of agricultural land leased under contracts (thsd. ha) showed a coefficient of 0.024359 ($t = 0.67036$; $p = 0.51354$; $R^2 = 0.38536$), while wheat yield (centner/ha) had a coefficient of 0.0013061 ($t = 0.19909$; $p = 0.84506$; $R^2 = 0.54912$). Peas demonstrated a relatively stronger effect with a coefficient of 0.18311 and a t-value of 1.6683 ($p = 0.11745$; $R^2 = 0.57495$). Barley yield contributed modestly (0.0053723; $t = 0.40772$; $p = 0.68964$; $R^2 = 0.47749$). The area of all agricultural holdings (thsd. ha) had a negative coefficient of -0.059483 ($t = -1.5805$; $p = 0.13631$; $R^2 = 0.38705$), while private farms (thsd. ha) showed a positive and statistically significant effect with a coefficient of 0.097974 ($t = 2.3439$; $p = 0.034361$; $R^2 = 0.59283$). Household land area (thsd. ha) had a negligible impact (-0.00023671 ; $t = -0.0072452$; $p = 0.99432$; $R^2 = 0.43447$). Lastly, the harvested area of all agricultural holdings (thsd. ha) was associated with a coefficient of 0.047728 ($t = 1.0755$; $p = 0.30035$; $R^2 = 0.45299$). Effect heterogeneity is consistent with biological and organizational channels: legumes (peas) show larger sensitivity to microclimate benefits, while structural variables (private farms) proxy management intensity and adoption capacity. The negative sign on "area of all holdings" suggests composition or diminishing returns at scale without commensurate investment. Overall, structure and management quality appear to mediate how shelterbelts convert biophysical gains into measurable outcomes—an argument for pairing shelterbelt programs with managerial and credit support.

Table 4. The multiple linear regression analysis for studied parameters.

Variables	Coeff.	Std.Err.	t	p	R ²
Constant	9.321	45.035	0.20697	0.83901	
The total area of agricultural land leased under contracts, thsd. ha	0.024359	0.036337	0.67036	0.51354	0.38536
Wheat, centner/ha	0.0013061	0.0065606	0.19909	0.84506	0.54912
Peas, centner/ha	0.18311	0.10976	1.6683	0.11745	0.57495
Barley, centner/ha	0.0053723	0.013176	0.40772	0.68964	0.47749
All agricultural holdings, thsd. ha	−0.059483	0.037635	−1.5805	0.13631	0.38705
Including private farms, thsd. ha	0.097974	0.0418	2.3439	0.034361	0.59283
Households, thsd. ha	−0.00023671	0.032672	−0.0072452	0.99432	0.43447
Harvested area of all agricultural holdings, thsd. ha	0.047728	0.044379	1.0755	0.30035	0.45299

Data present the correlation coefficients as of 2023 between the area of shelterbelt forest plantations and various agricultural production indicators. The area of forest shelterbelts showed a correlation of 0.73 with the total area of agricultural land leased under contracts. Crop yields were positively associated, with coefficients of 0.78 for wheat, 0.80 for peas, and 0.73 for barley. Regarding land use, the correlation with all agricultural holdings was 0.73, with private farms reaching a higher value of 0.87, and households at 0.71. For cereals and leguminous crops, the harvested area of all agricultural holdings correlated at 0.78 with shelterbelt area (Table 5). The higher association for private farms relative to households indicates that complementary inputs (seed quality, timing, machinery) amplify shelterbelt benefits. The strong link with harvested area suggests risk reduction keeps marginal land in production, especially under weather variability. These patterns support targeted incentives—maintenance subsidies and extension services for farms most able to internalize and scale the gains—while community programs can help households overcome adoption barriers.

Table 5. Correlation coefficients between the area of shelterbelt forest plantations and agricultural production as of 2023.

Indicator Name		Area of Forest Shelterbelts, thsd. ha
		R
The total area of agricultural land leased under contracts, thsd. ha		0.73
Yields	Wheat, centner/ha	0.78
	Peas, centner/ha	0.80
	Barley, centner/ha	0.73
	All agricultural holdings, thsd. ha	0.73
Planted area under annual and biennial agricultural crops	Including private farms, thsd. ha	0.87
	Households, thsd. ha	0.71
	Harvested area of all agricultural holdings, thsd. ha	0.78
Cereals and leguminous crops		

Source: own calculations.

The Neighbor-Joining (NJ) clustering method applied to administrative areas of Ukraine provides a hierarchical representation of regional similarities based on selected socio-economic or environmental indicators. This approach constructs a tree-like diagram where each branch represents an oblast (region), and the length of the branches reflects the degree of dissimilarity between them. Regions that are more similar cluster closer together, while those with distinct profiles appear farther apart. In the NJ tree, oblasts such as Dnipropetrovska, Odeska, Zaporizka, and Mykolaivska may form a tight cluster, indicating shared characteristics—possibly in terms of agricultural structure, climate, or land use.

Meanwhile, regions like Zhytomyrska, Khmelnytska, and Kyivska might group separately, suggesting a different set of attributes (Figure 2). Branch lengths imply differences are not purely climatic. Tenure, input access, market connectivity, and shelterbelt network condition likely contribute. Hence, region-specific packages are warranted: windbreak expansion and maintenance in agro-steppe clusters; erosion-control belts and riparian buffers in forest-steppe; and quality upgrades (rejuvenation, species mix, continuity) where belts exist but underperform (Figure 3). Clustering thus offers a practical map for prioritizing limited public funds along the highest benefit–cost frontiers.

The administrative units with the largest areas of protected agricultural land by shelterbelt forest plantations were defined, including: Losiatynska—3843.9 ha, Marianivska—2794.68, Kovalivska—2703.87 ha, Xaverivska—2533.13 ha, Hrebinkivska—2433.24 ha, Yatskivska—2381.73 ha, Polohivska—2197.22 ha and others. The smallest area of protected forested land is concentrated in the following administrative units Varovitska—33.39 ha, Lubyanka—55.01 ha, Dzvinkovskaya—198.57 ha, Ivankovychivska—211.81 ha, Zdorovska—212.49 ha, etc. The distribution signals widening resilience gaps: high-coverage communities can compound gains through yield stability and reduced soil loss, while low-coverage areas remain vulnerable to wind erosion and moisture stress. From a targeting perspective, minimal coverage offer high marginal returns to initial planting, especially where belts can connect fragmented fields. In high-coverage areas, returns will hinge more on quality upgrades—belt rejuvenation and corridor continuity—than on simple area expansion (Figure 4).

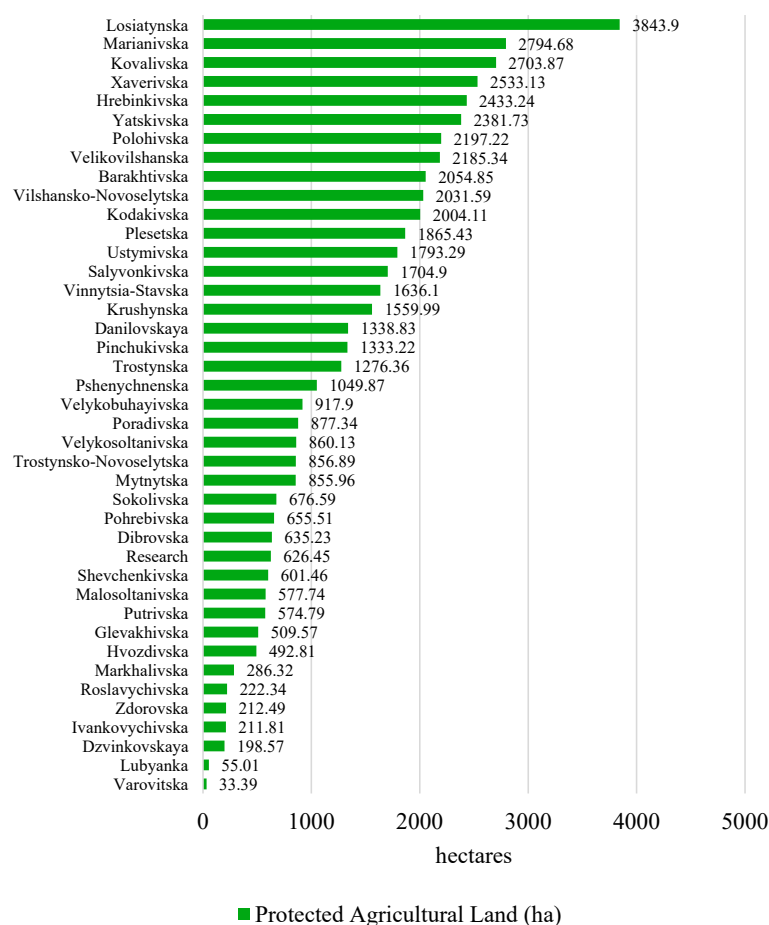


Figure 4. Diagrams of the area of protected agricultural land by shelterbelt forest plantations by administrative units in Vasylykiv district of the Kyiv region in Ukraine. Source: compiled by the authors.

4. Discussion

4.1. Deforestation Drivers and Land Use Policy: A Statistical Analysis of EU and Ukrainian Forestry Trends

Looking more broadly across countries, production growth often goes hand in hand with pressure on forest resources, but this pressure can be moderated when growth comes from efficiency gains rather than simply expanding harvests. In practice, that means getting more value from each worker and each unit of capital, not just cutting more trees. For policy, two directions follow. First, at the farm level, expand and maintain shelterbelts while supporting good management—advice, credit, and upkeep—so producers can fully benefit. Second, at the regional level, focus on efficiency and careful stewardship in areas with large commercially valuable forests to keep losses in check. We note limits of the current design and encourage future work that tracks changes over time to better pin down cause and effect.

In 2020, researchers analyzed how Ukraine could develop sustainable land use through better planning and policy reforms [47]. The analysis of the our results showed that the extent of deforestation in EU countries did not significantly depend on population size ($R = 0.09$), a finding that held particular importance given the global trend of population growth, which reached 7.53 billion people in 2018 according to the World Bank [48]. The relationship between forest loss and the form of forestry land ownership revealed equal absolute correlation values but opposite signs ($R(X4) = -0.36$; $R(X5) = 0.36$), indicating that ownership type—public or private—did not influence the reduction in forest area (Table 1). Instead, deforestation in the EU was primarily regulated by compliance with forestry legislation, strong institutional support, pan-European forest monitoring systems, and the implementation of international environmental programs aimed at reducing CO₂ emissions. Limits on farming land use were set to protect water resources. These actions matched global sustainability goals and helped Ukraine move toward joining the EU. Officials created buffer zones and coastal barriers to guard waterways and reduce pollution [49].

Forest cover loss did not significantly affect employment growth in the forestry sector ($R(X10) = 0.47$), largely due to the widespread use of robotic automation and labor-saving technologies. A strong correlation was observed between forest stand destruction (Y) and geographical indicators such as country area ($R(X2) = 0.62$), forest area ($R(X3) = 0.89$), and forest land suitable for commercial production ($R(X6) = 0.85$), confirming that countries with larger forested regions tended to experience greater forest loss. Economic factors also showed notable correlations with deforestation, including total production of forestry goods and services at actual prices ($R(X7) = 0.53$), gross value added at basic prices ($R(X8) = 0.80$), and gross increase in fixed capital investment in forestry ($R(X9) = 0.91$), suggesting that forest loss had a tangible impact on the economic development of the sector. Additionally, forest cover loss affected labor productivity, as reflected in performance indicators such as volume of felled trees per employee ($R(X12) = 0.52$) and gross value added per employee ($R(X13) = 0.71$), both of which directly depended on economic output. The matrix analysis enabled the identification of key factors correlated with the performance indicator (Y), and based on these findings, additional performance indicators were proposed to support the monitoring and sustainable management of forestry land, as outlined in Table 2.

The hierarchical clustering method applied to Ukraine's regions revealed distinct groupings shaped by geographical, socio-economic, and cultural similarities. Western regions such as Lvivska, Ivano-Frankivska, and Zakarpatska clustered together due to their shared historical ties, while central regions including Kyivska, Zhytomyrska, and Khmelnytska demonstrated common economic structures. Eastern Ukraine, represented by Donetska and Luhanska, formed a separate cluster reflecting unique socio-economic conditions, and southern regions like Odeska, Mykolaivska, and Khersonska were grouped

based on coastal influences. The regression analysis showed that private farms significantly influenced the dependent variable, as evidenced by a statistically significant positive relationship ($p = 0.034$). This suggested that private farms contributed to agricultural productivity through optimized land use and crop selection, playing a vital role in sectoral efficiency. crop rotation is essential for sustainable agriculture in Ukraine. It improves soil health, boosts food security, and reduces reliance on imports [50].

Alternatively, their impact may have been driven by broader economic dynamics, such as market-oriented agricultural policies or structural advantages over larger holdings [51]. The yield of peas had a moderately positive effect, though it lacked statistical significance, while other variables—such as wheat yield, barley yield, and leased agricultural land—displayed weak correlations, indicating limited influence within the model. The high p -value for households ($p = 0.994$) implied their negligible role. The R^2 values reflected moderate explanatory power, suggesting that further refinement of the model or inclusion of additional predictors could have improved its accuracy (Table 4).

4.2. Forest Shelterbelts and Farm Structures: Drivers of Agricultural Output in Ukraine

Our findings point to a clear story: shelterbelts help farms perform better by reducing weather risks and improving field conditions. Higher yields for wheat, peas, and barley are consistent with less wind damage, lower moisture loss, and better protection against erosion. The strong link with the area planted to annual and biennial crops suggests that farmers feel safer to sow and keep land in production when fields are protected. We also see that farm organization matters: private farms appear to turn these biophysical benefits into measurable results more effectively, likely because they can invest in timely operations, inputs, and maintenance of the belts.

The hierarchical clustering method that was applied to Ukraine's regions revealed distinct groupings shaped by geographical, socio-economic, and cultural similarities; western regions such as Lvivska, Ivano-Frankivska, and Zakarpatska were clustered together due to their shared historical ties, while central regions including Kyivska, Zhytomyrska, and Khmelnytska demonstrated common economic structures, eastern Ukraine—represented by Donetska and Luhanska—formed a separate cluster reflecting unique socio-economic conditions, and southern regions like Odeska, Mykolaivska, and Khersonska were grouped based on coastal influences. The regression analysis showed that private farms had significantly influenced the dependent variable, as evidenced by a statistically significant positive relationship ($p = 0.034$, which suggested that private farms had contributed to agricultural productivity through optimized land use and crop selection, playing a vital role in sectoral efficiency (Table 4). Alternatively, their impact might have been driven by broader economic dynamics, such as market-oriented agricultural policies or structural advantages over larger holdings [43,50]. The yield of peas had demonstrated a moderately positive effect, though it had lacked statistical significance, while other variables—such as wheat yield, barley yield, and leased agricultural land—had displayed weak correlations, indicating limited influence within the model. The high p -value for households ($p = 0.994$) had implied their negligible role, and the R^2 values had reflected moderate explanatory power, suggesting that further refinement of the model or inclusion of additional predictors could have enhanced its accuracy (Table 3).

Based on the correlation matrix provided in Table 5, several key relationships between forest shelterbelts and agricultural production were identified. A correlation coefficient of 0.73 between the area of shelterbelts and the total area of agricultural land leased under contracts indicated a strong positive relationship, suggesting that regions with more extensive shelterbelt coverage tended to have higher levels of land leasing for agricultural purposes. This pattern likely reflected the enhanced attractiveness of these areas due

to improved microclimatic conditions and increased land productivity [53]. The area of shelterbelts also showed a strong correlation with crop yields, particularly for wheat, peas, and barley, with coefficients of 0.78, 0.80, and 0.73, respectively. These findings suggested that shelterbelts had a substantial positive impact on crop productivity, with the strongest effect observed in pea yields, likely due to benefits such as reduced wind damage, better soil moisture retention, and protection against erosion. Additionally, a correlation coefficient of 0.87 between shelterbelt area and the area planted under annual and biennial crops, including those on farms, emphasized the role of shelterbelts in shaping agricultural land use. This very strong relationship implied that larger shelterbelt areas were associated with broader cultivation of diverse cropping systems, as shelterbelts created more favorable growing conditions [51]. Overall, the results supported the hypothesis that forest shelterbelts positively influenced agricultural production and highlighted their potential as a strategic tool for enhancing agricultural outcomes and promoting sustainable land management in Ukraine [52]. Nonetheless, it was acknowledged that other factors such as soil quality, climate conditions, and farming practices might also contribute to these observed relationships [53].

Satellite data served as the primary and, in many cases, the only reliable source of forest monitoring in regions of eastern Ukraine affected by active hostilities, particularly during the 2022–2023 [54].

The variation in the area of agricultural land protected by shelterbelt forest plantations across different administrative units is largely due to differences in land use planning, regional priorities, and historical patterns of shelterbelt implementation [48]. In regions such as Losiatynska, Marianivska, and Kovalivska, which have the largest areas of protected land, shelterbelt plantations have been more extensively integrated into the agricultural landscape. This widespread coverage significantly improves crop yields by creating a favorable microclimate, reducing wind erosion, and enhancing soil moisture retention. On the other hand, in units like Varovitska and Lubyanka, with minimal shelterbelt coverage, the protective benefits are limited, leading to less optimized agricultural productivity. These data make it possible to calculate the additional income generated by the agroforestry impact, as the enhanced yields directly contribute to increased profitability for local farmers. These insights underline the economic value of expanding shelterbelt networks to maximize their positive effects on agricultural output [55].

According to the results of the study, which utilized geoinformation modeling, the total area of agricultural land protected by shelterbelt forest plantations in the experimental site amounts to 51.66 thousand hectares. The modeling allowed for precise identification of the regions where these shelterbelts provide protective benefits to agricultural fields, effectively improving their productivity. The agroforestry impact, specifically on grain crop yields, was found to be 4 centners per hectare [29], demonstrating the significant role these plantations play in enhancing agricultural outcomes. The protection offered by these shelterbelts improves the microclimate for crops, reducing erosion and maintaining soil moisture, which leads to increased yields [56].

In terms of total productivity, the agroforestry effect generated by the field protection forest plantations within the experimental site amounts to 206.64 thousand centners of additional grain yield. This substantial increase in crop production underscores the economic value of shelterbelts, as the higher yields translate into greater agricultural profitability. The data provide clear evidence that the presence of forest shelterbelts contributes directly to the financial benefits for farmers by improving crop performance and resilience, especially in regions where these protective plantations cover significant portions of agricultural land [57].

Given the average price of agricultural products sold by enterprises, specifically cereals and leguminous crops, at 12.23 euros per centner (according to the State Statistics Service of Ukraine [58]), the economic impact of shelterbelt forest plantations is substantial. With the additional 206.64 thousand centners of grain yield attributed to the agroforestry effect of these plantations, the total economic benefit can be calculated. Multiplying the extra yield by the price per centner results in a potential economic effect of approximately 2527.21 thousand euros per year.

This figure highlights the significant financial advantages provided by shelterbelt forest plantations, as they not only improve crop yields but also translate into tangible economic gains for farmers and agricultural enterprises [58]. By enhancing agricultural productivity through improved environmental conditions, these plantations offer a sustainable method for increasing income in rural areas while promoting long-term land use efficiency and resilience [59]. Global wheat production is increasingly vulnerable due to climate change, energy instability, and geopolitical disruptions [60]. The EU has responded by reassessing agricultural strategies to mitigate supply chain risks [61]. In Ukraine, simplified and specialized farming practices have raised sustainability concerns, prompting calls for more diverse crop rotation systems [62]. As Ukraine deepens its integration with the EU, its agricultural sector faces both opportunities and challenges, including the need to align with EU standards and strengthen agri-food governance [63]. Rural development remains uneven, highlighting the importance of inclusive policies that support both modernization and regional equity [64]. Ukraine's forest ecosystems are facing increasing environmental pressures. Protective forest belts established decades ago in the Forest-Steppe have deteriorated ecologically, reducing their effectiveness in safeguarding agricultural landscapes [65]. In the north-eastern part of Zhytomyr Oblast, forest fires have emerged as a major threat, accelerating deforestation and ecosystem degradation [66]. A new assessments by the State Forestry Agency indicate that Ukraine's forest fund covers approximately 9.6 million hectares, with some positive trends in forest regeneration [61]. However, the presence of highly flammable fuels such as litter, duff, and herbaceous layers in coniferous forests of Polissia increases the risk of fire outbreaks. Advanced modeling techniques, including random forest algorithms, are being applied to understand fuel variation and guide fire prevention strategies [67]. In the broader context of sustainable agriculture and environmental resilience, recent findings on water resource pressure and nitrogen balance in the EU add critical insight. The 2025 study on EU agricultural land highlights how crop production directly affects surface and groundwater quality, emphasizing the need for better nutrient management [68]. This is particularly relevant for Ukraine, where intensified farming and simplified crop systems risk exacerbating nitrogen runoff and water stress. Shelterbelt forest plantations in Ukraine show strong positive correlations with agricultural productivity. As of 2023, their presence is linked to higher yields of wheat ($r = 0.78$), peas ($r = 0.80$), and barley ($r = 0.73$), and greater planted and harvested areas, especially among private farms ($r = 0.87$). These findings highlight the ecological and economic value of shelterbelts in supporting sustainable agriculture (Table 5). Recent research highlighted how healthy soils contribute to biodiversity and support green areas [69]. These insights were especially important for farming in Ukraine and Europe, where damaged soils reduced both crop performance and environmental quality. Overall, sustainable forest management and ecosystem service enhancement are critical to preserving Ukraine's forest resources amid climate and human-induced challenges.

5. Conclusions

The results of this study demonstrate that shelterbelt forest plantations significantly enhance agricultural productivity, particularly in terms of grain crop yields, which is also

confirmed by correlation analysis (0.87). Based on geoinformation modeling, the total area of agricultural land protected by shelterbelts in the experimental site is 51.66 thousand hectares, resulting in an additional 206.64 thousand centners of grain yield annually. Given the average price of 12.23 euros per centner for cereals and leguminous crops, the total economic impact of shelterbelts amounts to approximately 2527.21 thousand euros per year. These findings underscore the substantial financial benefits that shelterbelt plantations provide, contributing not only to increased crop production but also to the overall profitability of agricultural enterprises.

In practice, our results mean that shelterbelts are a low-cost way to raise and stabilize crop yields while keeping more land productively used. Farmers can start with repairing gaps in existing belts, replanting missing rows, and maintaining spacing to protect fields. Local authorities can co-finance seedlings and basic upkeep. Communities can use GIS maps to target streets, field edges, and erosion-prone areas where belts will bring the biggest gains first. For regions with large, commercially valuable forests, the priority is to grow by efficiency—better machinery, training, and planning—rather than by expanding harvests.

The results obtained can be directly used in spatial planning and the formation of sustainable development policies for territories. The identified relationships between the condition of forest stands, forest belts and land use indicators justify the inclusion of protective green corridors in community land use plans, climate change adaptation programs and strategies for the restoration of degraded land. In practice, this can be achieved through the integration of forest elements into master plans, zoning, local biodiversity conservation plans, and economic incentives for land users who support the ecological balance of landscapes. This approach promotes the integration of environmental and economic interests within spatial policy.

Moreover, shelterbelts, once established, are among the most cost-effective agronomic practices for enhancing crop growth. Unlike other agricultural inputs that require regular investment, such as fertilizers or irrigation systems, shelterbelts offer long-term benefits with minimal ongoing costs. They improve soil moisture retention, reduce wind erosion, and create favorable microclimatic conditions, all of which boost crop yields sustainably. Thus, shelterbelts represent a low-cost, high-return investment for farmers, making them an essential component of sustainable agriculture and land management practices in Ukraine. The developed models enable to model (estimate) the probable volume of forest cover loss in EU countries, to determine the total production of forestry goods and services at actual prices, value added (at actual prices) in the forest sector of the EU member states. Similar regression equations enable to model a management policy for the rational, ecological and economic use of forestry land in EU member states, taking into account the changes in factors that affect the performance indicator.

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