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Economic Assessment and Management of Agroforestry Productivity from the Perspective of Sustainable Land Use in the South of the Russian Plain

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Abstract: Recent international climate documents emphasize the great importance of the afforestation of agricultural land having a positive impact on CO_2 levels, not only by absorbing carbon by trees, but also by replacing fossil fuels with biomass. In Russia, until recently, the importance of forest plantations in the production of wood was underestimated, which created the problem of its accounting and effective management. When justifying modern protective afforestation programs, ambiguity in the estimates of tree productivity of plantings is one of the reasons for significant uncertainty regarding their impact on the energy security of the country. The purpose of this study was to undertake an economic assessment and assess the regularities of the dynamics of tree productivity of protective forest plantations on the flat terrain and slopes of the forest-steppe zone in the south of the Russian Plain for the effective management of agroforestry taking into account environmental aspects. At the level of the simulation unit—the protective forest cover of the agricultural territory—the main forest reclamation strategies were modeled from the perspective of sustainable land use, depending on the type of relief, the level of forest protection of land and the erosive state of soils. These models comprehensively analyzed the wood productivity of the main forest-forming species, which differ in functionality and service life. It is established that the productivity of 1 ha of forest stands in the forest-steppe is 320–400 m^3 of wood, and the commercial effect of its harvesting is EUR 14675–EUR 56567. The specific (per 1 ha of land use) wood productivity of trees on flat terrain increases with the growth of forest protection of the site (due to the reduction of inter-band space) by 1.2–1.8 times. On the slopes, with an increase in their steepness, the specific effect of harvesting wood also increases by almost twofold. On steep slopes with highly eroded soils, the efficiency of forest reclamation decreases by 23%–24% due to a decrease in the width of forest stands and the inclusion of a hydraulic element in their systems. The use of long-lasting forest-forming species for all forest reclamation strategies is more profitable than the use of fast-growing species—the value of the specific average annual (discounted) income per 1 ha of the agroforest landscape is, respectively, EUR 427–EUR 970 and EUR 166–EUR 545. The study will confirm the need to finance forest reclamation measures not only to ensure sustainable rural development, but also Russia's qualitative transition to a low-carbon economy.

Keywords: agroforestry; forest-forming rocks; productivity; protective forest cover; economic evaluation; commercial effect

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1. Introduction

Currently, there is an urgent need in Russia to revitalize farming systems and to reduce the burden on regional natural capital. This creates prerequisites for the development of forest reclamation of agricultural lands, in the development of protective afforestation programs. When growing forest stands, first of all, their soil protection efficiency is taken into account [1], which does not require discussion. At the same time, in the forest-steppe zone, where forest-growing conditions are generally favorable for the successful cultivation

of many types of woody vegetation, the quality of the emerging stands is also of great importance in terms of their forest resource value, which consists of increasing the mass of wood products. This is especially relevant now, when the imperative of a rational use of forest resources in the European area is being promoted in the country. The recent sharp increase in prices for building materials and biofuels from wood also plays a role in the increased importance of agroforestry in the country.

World experience shows that agroforestry is a long-term global strategy for sustainable land use, which has a high efficiency [2,3]. It is widely recognized as a land-use practice capable of producing biomass for the production of bioenergy and biofuels, but very little information is available on this topic [4]. The sustainable supply of biomass in the world is still a serious problem [5].

In the United States, agroforestry is the most promising form of ensuring sustainable biomass production without compromising grain production in the North-Central region (Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, South Dakota, and Wisconsin). This region is home to some of the most productive agricultural land in the world, and biomass production in this area is crucial for the purposes of the Biomass Research and Development Technical Committee (BRDTC) [5]. From a biological point of view, the cultivation of perennial biomass within the existing acreage of this region is ideal, but the inclusion of an agroforestry system for biomass production in the traditional agricultural model in this region is a difficult task that will require agricultural producers to overcome logistical, financial and cultural obstacles [6].

In recent years, the European Union has been paying increasing attention to supporting and encouraging actions to combat climate change, which are also aimed at achieving greater energy efficiency. It has been proved that agroforestry, at the expense of wood resources, can lead to less dependence on imports and an increase in added value for rural areas. The economic and social interest in renewable energy sources and bioenergy is mainly due to the possibility of easier achievement of energy self-sufficiency levels and significant replacement of the use of fossil fuels [7].

The indicators of the production of stem wood of several forest species has dominated studies of the productivity of agroforestry plantations in most areas of Australia with low and medium rainfall [8].

In Russia, in modern natural and economic conditions, the justification of the importance of protective afforestation as a source of wood and biofuels is difficult [9,10]. Specialists in the field of agriculture and forestry often lack informational resources and a professional base for an adequate assessment of the effectiveness of this type of economic activity and its inclusion in farm systems. First of all, there is a shortage of modern scientific papers that would work out the issues of assessing wood resources with optimal spatial placement of forest plantations in the agricultural landscape at the regional level from the perspective of sustainable nature management and the latest scientific achievements. The few available studies of the period of the second half of the last century relating to the period of the planned economy have lost relevance in the conditions of transition to a low-carbon economy [11–13].

Currently, all over the world, as well as in Russia, the approach to protective afforestation has changed—ecosystem goods and services of stands are taken into account when determining its effectiveness [14–16]. Despite the fact that this definitely complicates the assessment of the effectiveness of protective forest plantations, at the same time, it contributes to the formation of a new concept of sustainable forest-reclaimed land use [17–19].

A number of factors indicate the significant potential of agroforestry in the forest-steppe zone. These include a variety of agricultural lands in the region, deflation-dangerous winds, precipitation causing harmful runoff, uneven terrain, as well as the need to solve a number of environmental and economic problems associated with rural land use [20].

The article is based on an approach to assessing the wood efficiency of forest plantations from the perspective of sustainable land use. The proposed methodology is to measure the effectiveness of forest plantations not by the actual productivity of 1 hectare

of forest, which, due to lack of care, may not always be in satisfactory condition. Instead, the new approach is supplemented by modeling several options for the placement of forest plantations in the agricultural landscape and determining the productivity of forest plantations per 1 ha of the plot. The analysis of productivity dynamics on these models, depending on the factors forming it, will allow us to develop a scenario forecast of the commercial effect of harvesting wood products with different strategies of afforestation of flat and sloping lands, which, with proper care of the forest, it will be possible to obtain in the future (by the period of reforestation). Discounting commercial effects will allow for bringing their value to the average annual values for comparative analysis of rocks of different service life.

The main purpose of this study was to analyze the tree productivity of protective forest stands, as well as to determine the patterns of its dynamics for effective management of afforestation of agricultural land on flat and uneven terrain, taking into account environmental aspects and sustainable land use.

2. Materials and Methods

2.1. Case Study Sites

The studies were carried out in relation to flat and uneven terrain located within the forest-steppe natural zone. This zone is located in the northern part of the Saratov region and is confined to the south of the Russian Plain (Figure 1). It is an asymmetric plateau dissected by erosion, steeply descending towards the Volga River. The plain type of terrain is well developed only in its western, lower part. The slope type of terrain is developed along the high bank of the Volga River.

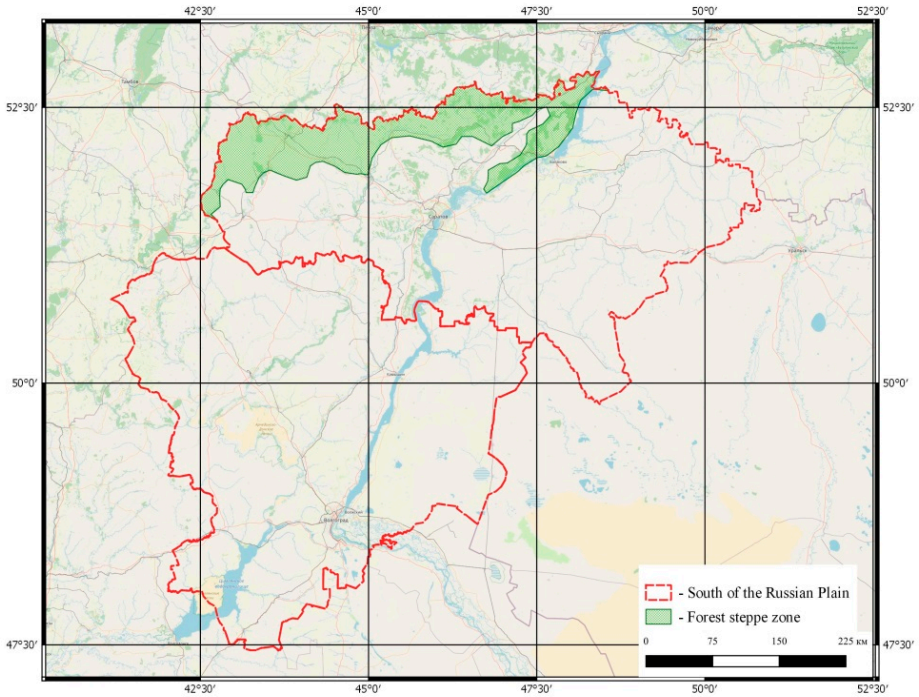


Figure 1. Geographical location of the forest-steppe zone in the south of the Russian Plain.

The forest-steppe zone is characterized by the dominance of gray forest soils. There are also podzolized and leached chernozems. Gray forest soils are located mainly in the central and southeastern regions of the zone. The bulk of humus substances in these soils is concentrated in the upper layer of 15–20 cm in size. The humus content is 4.2%. According to the content of mobile forms of nutrients such as nitrogen, phosphorus, potassium, gray forest soils are considered sufficiently resourceful—with, respectively, 32, 52 and 220 mg kg^{-1} [21].

The climate of the forest-steppe zone is mid-continental (the coefficient of continentality is equal to 166–184), which manifests itself in moderately mild and moderately cold winters and moderately warm summers. The sum of active temperatures is 2000–2800 °C. 400–600 mm of precipitation falls per year. According to the annual moisture content, the forest-steppe zone is characterized as semi-humid—the moisture coefficient is 0.35–0.045 [22].

The territory of the forest-steppe zone is annually exposed to strong erosive effects of meltwater. Wind erosion in plowed areas is also a destructive natural process [23,24].

2.1.1. Structure of Forest Stands and Their Productivity

On the plains of the watershed fund of lands (with a slope of up to 2.0°), windbreak forest stands are created from tree species adapted to forest-growing conditions. The main strips are placed parallel to each other, perpendicular to the direction of the most harmful winds prevailing in this territory [25]. From precocious species for forest-steppe, Hanging birch (*Betula pendula* Roth.) is recommended for planting, from durable species—Petiolate oak (*Quercus robur* L.) [26].

On slopes with a steepness of 2.1–6.0°, runoff-regulating forest strips are created. Protective afforestation in conditions of uneven terrain has a different specificity in the productivity of stands. Here, the influence of the orographic factor requires replacing the forest-forming rocks recommended for plakors with rocks that are less demanding of soil fertility, since it is necessary to work more or less with washed-away soils. Experience shows [27] that not all tree species grow well on such soils. Therefore, when creating forest plantations on the slopes, they focus primarily on the quality of the land and the local forest growing conditions in which it is planned to grow tree crops.

So, Poplar is a recommended fast-growing breed for the afforestation of slopes. Silver poplar is preferred in protective afforestation (*Populus alba* L.), as a tree species characterized by the greatest resistance to diseases and natural anomalies. In addition, its commercial wood has a higher quality than the wood of other poplars.

Instead of oak on washed-out soils of medium and strong intensity, Siberian larch (*Lárix sibírica*) is successfully used in protective afforestation. Despite the fact that this breed is inferior to oak in terms of wood hardness, it is a long-lasting wood crop that is low—demand for soil fertility.

Based on special studies [27–29], a comparative analysis of the productivity of the main forest-forming species adequate to the forest-growing conditions of the forest-steppe zone in the south of the Russian plain was carried out.

2.1.2. Technological Parameters of the Placement of Protective Forest Stands within the Agricultural Landscape

It is possible to manage the tree productivity of forested land use on the plain by adjusting the distances between windbreak protective plantings. It is known that they are a function of climate, and effective protection of fields is provided by 3–4-row forest strips with a total width of 9–12 m meters [30].

In accordance with the instructions in place in Russia [31], the plantations of Hanging birch are created by planting 1-year-old seedlings in the form of clean plantings from 3 rows. Seating capacity 3.0 m × 1.5 m. The total width of the plantings with edges is 9 m. The Hanging birch is a fast-growing precocious breed. The closing period of the tree crowns begins at the age of 7. The operational service life of the plantation before reforestation is 35 years.

The plantings of the Petiolate oak is performed by sowing seeds (acorns). To ensure the stability of oak forest crops, accompanying hardwoods are introduced into the extreme rows of plantings. The placement of plants is 3 m × 1.5 m, between the holes of the oak—0.9 m. The total width of 4 rows of forest strips is 12 m.

Petiolate oak grows relatively slowly, especially in the first years of life. The closing period of the tree crowns begins at the age of 10–12. The operational service period before reforestation in the forest-steppe is 50 years.

On the slopes, the influence of the orographic factor and the erosion hazard requires replacing the forest-forming rocks recommended for flat lands with rocks less demanding of soil fertility.

In accordance with the recommendations in place in Russia [32], the plantations of Silver poplar are created by planting 1-year-old seedlings in the form of clean plantings from 3 rows. Seating capacity is 2.5 m × 1.5 m. The total width of the enclosure with the edges is 7.5 m.

Silver poplar is a fast-growing precocious breed. The closing period of the tree crowns begins at the age of 5. The operational service life of the plantation before reforestation is 30 years.

Siberian larch plantings are created by planting 1-year-old seedlings from 3 rows. Seating capacity is 2.5 m × 1.5 m. The total width with the edges of the leaf-crown plantings is 7.5 m.

Siberian larch is a durable breed. The period of closing for the tree crowns begins at the age of 9. The operational service period before reforestation in the forest-steppe on washed-away lands is 50 years.

On strongly eroded steep slopes from 5.0° to 6.0° in the lower aisle of the forest strip, a device of the simplest hydraulic structures is provided, which, interfacing with flow-regulating forest strips, increases the efficiency of the latter by 1.5–4.0 times [33]. At the same time, the total width of the forest plantation is reduced to 6 m (2 rows). This naturally reduces productivity and net-cash flow from forested land use (by almost 25%), but at the same time increases the sustainability of land use and brings the environmental safety of agricultural production on the slopes to 100%.

2.2. Modeling of Systems of Protective Forest Stands and Land Use

An agroforest landscape implies the presence of protective forest plantations within its limits. Their spatial influence on the adjacent territory was analyzed using a system analysis [34] at the level of a simulation unit—protective forest cover (the ratio of the area of planted forests to the total area of the agricultural landscape).

The methodology for assessing the productivity management of forest reclamation facilities to increase their commercial effect was based on the consideration of environmental aspects. Thus, the adoption of the management decision on the effectiveness of the system of forest plantations was based on the optimal protective-forest cover of the site, at which safe land use is achieved.

Models of agroforestry complexes included various combinations of systems of protective forest plantations and land use. The main bioengineering parameters of these models (the range of forest-forming species adequate to the quality of the soil cover, the width and row of protective forest stands, inter-lane spaces, the number of forest stands on the site) were established on the basis of basic recommendations for afforestation of agricultural land [31,32,35].

The constructed engineering and technological models of windbreak-forest strips imitated a variety of relationships “Flat terrain type—forest—land use”. The options for the placement of forest plantations with different distances between trees were analyzed. Thus, the security of the site was modeled at 50%, 68% and 100%. This “Windbreak” forest reclamation strategy is applicable to agricultural land with a slope steepness of up to 2.0°.

The constructed engineering and technological models of runoff-regulating forest strips imitated a variety of relationships “Slope type of relief—forest—land use”. Different options for the placement of forest plantations on slopes with a steepness from 2.1 to 6.0° were Analyzed. “Runoff-regulating” forest reclamation strategies are applicable to the plowed slopes of watershed uplands (the network fund of lands enclosed between the fences and the hydrographic network [36]).

It should be noted that in the forest-steppe zone in the south of the Russian plain, the most widespread of erosive areas has a convex profile of catchments, taking the first place in prevalence among all types of profiles [37].

2.3. Data Collection

The quantitative assessment of the wood stocks of protective forest stands was based on the available evidence on the total stock of stem wood obtained from reforestation logging and its operational stock obtained during various maintenance and sanitary logging in the forest-steppe zone in the south of the Russian Plain [27,29,38].

The research was carried out on the basis of an extensive literature review, based on long-term field studies of the Departments of Ecology and Economics of the All-Russian Research Institute of Agroforestry (now the Federal Scientific Center of Agro-ecology, Complex Melioration and Protective Afforestation of the Russian Academy of Sciences).

These field studies were based on the laying of a stationary test area with the expectation that there would be at least 200 trees of the main forest-forming species within the area. Measurements and recalculations were carried out for this area, and the percentage of the sample of trees during care felling and reforestation was determined. Based on the recalculation of trees on the test areas and data on the volume of trunks determined by diameter and height, the stock of raw stem wood of the stand (m^3 ha^{-1}) by species was calculated. The stock of all raw wood was taken into account, as well as the selected care during various logging operations [28].

2.4. Data Analyses

2.4.1. Assessment of Forestry Efficiency of Protective Forest Stands (Per 1 ha of Trees)

Economic Assessment of the Productivity of Protective Forest Stands

To identify the spatial dynamics of wood productivity of forest plantations in the agricultural landscape, depending on the shape of the terrain, the initial amount of wood resources was calculated, which is actually obtained by the age of completion of the functional service of forest plantations from 1 hectare of trees. Within the framework of the accepted conditions, this amount of resources is set for each forest-forming breed studied ($Wood_{forest}$, m^3 ha^{-1}). It was calculated as the sum of the volumes of stem wood obtained from reforestation ($Wood_{Stem}$), wood obtained from sanitary logging ($Wood_{Sanit}$) and wood waste ($Wood_{Waste}$).

$$Wood_{forest} = Wood_{Stem} + Wood_{Sanit} + Wood_{Waste} \quad (1)$$

The profit from the sale of wood products from 1 ha of trees that have reached the age of reforestation (Profit, EUR) is calculated according to the following formula:

$$Profit = Wood_{Stem} \times K_1 \times P_1 + Wood_{Stem} \times K_2 \times P_2 + Wood_{Sanit} \times K_1 \times P_1\ Wood_{Sanit} \times K_2 \times P_2 \quad (2)$$

In the formula, K_1 is the specific weight of business wood, %; P_1 is the selling price of round wood, EUR; K_2 is the specific weight of wood;%; P_2 is the selling price of firewood, EUR.

The formula for calculating the net profit from the sale of wood resources obtained from 1 ha of forest plantations that have reached the age of reforestation (Net Profit, EUR) is as follows:

$$Net\ Profit = Profit - C_1 - C_2 \quad (3)$$

In the formula, C_1 is the cost of harvesting wood and biofuels during reforestation (determined by the standard operating calculation and technological maps for single-intake continuous felling [39]), EUR; C_2 is the cost of harvesting wood and biofuels during selective sanitary felling (determined by the standard operating calculation and technological maps for the removal of up to 30% of trees in the plantation), EUR.

The costs and commercial effects of harvesting wood products in protective forest plantations were obtained for prices in 2021. They were determined in Russian rubles and converted into euros at the official exchange rate set by the Central Bank of Russia, Moscow, Russia, 10 December 2021.

2.4.2. Assessment of Forestry Efficiency of Land Use Equipped with a System of Protective Forest Stands (Per 1 ha of Agricultural Landscape)

Economic Assessment of the Productivity of Land Use Equipped with a System of Protective Forest Stands

The basis for assessing the specific productivity of agroforestry landscapes is the indicator of their protective forest cover [40].

The formula for evaluating the unit productivity of 1 ha of a landscape equipped with a system of protective forest plantations ($Wood_{landscape}$, m^3 ha^{-1}) has the following form:

$$Wood_{landscape} = Wood_{forest} \times S_{forest}/S_{Landscape} \quad (4)$$

In the formula, S_{forest} is total area of trees on the plot, m^2; $S_{Landscape}$ is total land use area, m^2.

The assessment of the unit-commercial effect of harvesting wood resources in forest plantations (Eff, EUR) was also conducted based on the specified forest cover of the landscape and has the following form.

$$Eff = Net\ Profit \times S_{forest}/S_{Landscape} \quad (5)$$

For a comparative analysis, two scenarios of forest-reclamation land-use development were developed for each strategy, both of which differ in the durability of forest-forming species—slow-growing long-lasting and fast-growing precocious. The assessment of their commercial effect in average annual terms ($\overline{Eff}$, EUR) was carried out according to the following formula.

$$\overline{Eff} = \sum_{1}^{T} Eff_t \times a / Effmax \sum_{1}^{T} \times a \quad (6)$$

In the formula, Eff_t is the commercial effect in the year t; Eff_{max} is the commercial effect of the forest strips that have reached the design height, EUR; a is the coefficient calculated according to the formula $(1 + r)^{-1}$; r is the discount rate, %; T is the functional service life of the plantation, year.

The dynamics of discounted commercial specific effects obtained from afforestation of land on a flat type of relief ($\overline{Eff}_1$) and hilly type of relief ($\overline{Eff}_2$) were studied using the following dependencies.

$$\overline{Eff}_1 = f\ (FPr,\ SL) \quad (7)$$

$$\overline{Eff}_2 = f\ (SS,\ SL) \quad (8)$$

In formulas, FPr is forest protection of land, %; SL is service life, year; SS is slope steepness, °.

3. Results

3.1. Assessment of Forestry Efficiency of Protective Forest Stands (Per 1 ha of Trees)

3.1.1. Structure of Forest Stands and Their Productivity

The following types of fast-growing and durable tree species are selected for protective afforestation (Figure 2).

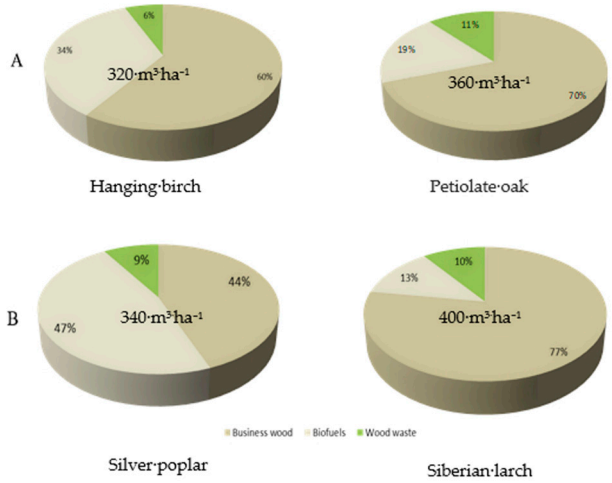


Figure 2. Structure and volume of wood products obtained by the period of reforestation in windbreak (**A**) and runoff-regulating (**B**) forest plantations (on average in the forest-steppe zone in the south of the Russian Plain).

It has been established that a fast-growing breed, the Hanging birch, is characterized by successful growth in all conditions of growth of the forest-steppe zone; it is of little use for soil fertility. On the plakors, by the age of reforestation, the Hanging birch in the system of forest plantations has satisfactory productivity (on average 320 m^3 ha^{-1}) and significant market value—the yield of business wood from birch stands is approximately 60%.

On the slopes, distinguished by successful growth in all orographic conditions of growth in the forest-steppe and forming large stocks of stem wood, birch stands on washed away soils are at the same time characterized by low marketability—business trees make up no more than 12%–22%.

To increase the forestry value of forest reclamation by twofold, poplar plantations can be used as an alternative to birch plantations on infertile soils. By the period of reforestation, poplar has not only large reserves of stem wood, but also high marketability of stands (in conditions of close occurrence of groundwater).

The maximum reserves of stem wood in the forest-steppe Silver poplar forms in narrow forest stands. Even in conditions of washed away soils, by the age of reforestation, on average, they reach a significant value—340 m^3 ha^{-1}.

Of the long-lasting species, the most promising forest-forming species is the petiolate oak. However, it is a very demanding breed for soil fertility. In the conditions of the flat terrain of the forest-steppe zone, with proper care, the Petiolate oak is characterized by successful growth. With age, the sorting structure of pure oak stands improves, but the yield of business wood by the period of reforestation usually does not exceed 50%. The marketability of the wood products of the oak is increased by introducing other hardwoods into the planting by up to 67%–71%.

As for the slope lands, the use of oak in protective afforestation is highly undesirable. This is due to the fact that the productivity of oak plantations is closely dependent on the growing conditions, whereby the greater the degree of soil washout, the worse the taxation indicators. Thus, at the age of 50, the average height of an oak plantation on unwashed soils is 18 m with an average diameter of 17.4 cm and stem wood reserves of 350 m^3 ha^{-1}, while on washed soils at the same age this measurement is 12 m, 11 cm and 130 m^3 ha^{-1}, respectively. In addition to reducing the grade of wood, stands on washed-away soils also have a high infection rate with various diseases.

In the conditions of the forest-steppe, the maximum reserves of stem wood are formed in narrow pure larch plantations on average 400 m^3 ha^{-1}. The timeliness of forestry care has a great impact on the quality index of larch wood. In plantings of 50 years of age, passed by one-reception care felling, business trees usually account for up to 90%. The absence of logging maintenance or their untimely occurrence leads to significant losses of

wood as a result of natural thinning and to a decrease in the marketability of stands up to 60%.

A comparative analysis of the median productivity of tree species recommended for the forest-steppe zone shows (see Figure 2) that the maximum volume of total wood stocks obtained by the period of reforestation in the forest-steppe zone is 14%–29% higher in long-lasting breeds than in fast-growing precocious breeds. In the general structure of stem wood, these forest-forming species are also more effective than fast-growing species, in terms of the content of business wood—70% (Petiolate oak) and 77% (Siberian larch). In general, in the forest-steppe zone, 1 hectare of protective forest stands on average accumulates 320–400 m^3 of wood over the entire operational life, which is a significant indicator of their forestry efficiency for the local economy.

The median marginal yield of wood during sanitary logging in windbreak and runoff-regulating forest strips averages 70–130 m^3 ha^{-1} (Figure 3). Around half of these reserves are brushwood and are not valuable products for land users. The share of business sortings is only 14%–23% of this volume.

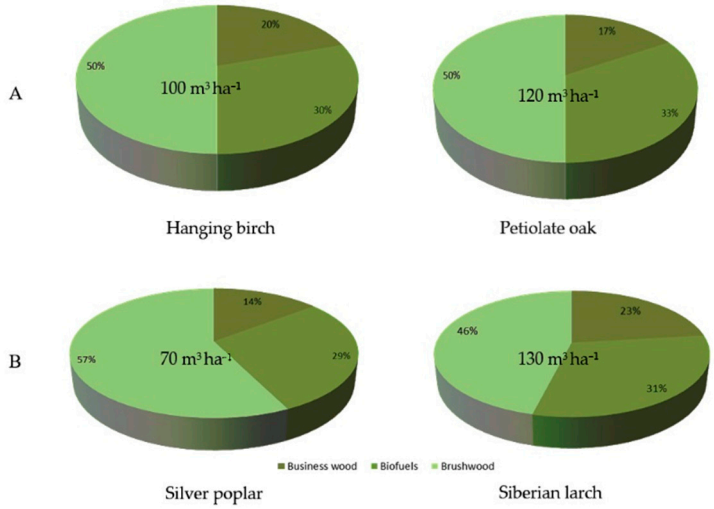


Figure 3. Structure and volume of wood products obtained from selective sanitary logging in windbreak (**A**) and runoff -regulating (**B**) forest plantations (on average in the forest-steppe zone in the south of the Russian Plain).

3.1.2. Economic Assessment of the Productivity of Protective Forest Stands

The costs of harvesting wood products obtained from logging depend on the complexity and manufacturability of operations.

Thus, during reforestation, measures include the continuous felling (100%) of trees with carburetor chainsaws with the abandonment of reliable undergrowth, cutting of shrubs and small woodlands, harvesting, skidding of branches and wood, cutting of wood obtained from felling the forest, collecting wood residues in rolls.

Carrying out selective sanitary felling includes measures for cutting down trees from the root up to 30% by the number of trunks with carburetor chainsaws, cutting wood obtained from felling the forest, collecting wood residues into rolls.

Calculations show (Table 1) that the cost of harvesting wood on flat terrain is EUR 271 with reforestation and EUR 114 with selective sanitary logging. Due to the complexity of technological operations and working conditions (from 362 to 471 machine-hour during reforestation and from 163 to 212 machine-hour with sanitary logging) on slopes from 2.1 to 6.0° costs increase by 30%.

Table 1. Resource estimate for harvesting wood in protective forest stands on flat terrain and slopes in the forest-steppe zone in the south of the Russian Plain.

Calculated Indicators	Unit of Measurement	Single-Intake Reforestation (Continuous Cutting of Trees from the Root 100% by the Number of Trunks)		Selective Sanitary Felling (Cutting Down Trees from the Root Up to 30% by the Number of Trunks)	
Slope steepness	degree	0.0–2.0	2.1–6.0	0.0–2.0	2.1–6.0
Tractors up to 59 kW (80 horsepower)	machine-hour	179.63	233.52	68.41	88.93
Carburetor chainsaws	machine-hour	122.60	159.38	86.62	112.61
Motor-cutters	machine-hour	9.40	12.22	x	x
Grubbers-gatherers with a tractor up to 79 kW (108 horsepower)	machine-hour	42.61	55.39	x	x
Wood residue fellers	machine-hour	7.70	10.01	7.70	10.01
Forestry workers	man-hour	706.01	917.81	338.07	439.49
Machinists	man-hour	231.64	301.13	70.76	91.99
Total costs	EUR	EUR 271	EUR 352	EUR 114	EUR 149

The commercial effect of harvesting wood in protective forest stands is expressed in the form of profit from the sale of wood products and depends on the quality and marketability of stands (Table 2). Both on flat terrain and on sloping terrain, the maximum profit from the sale of wood to the land user will be achieved by the cultivation of durable forest-forming species. By the period of reforestation, within the framework of the accepted conditions, 1 ha of forest plantations will provide net income in the amount of UER 45987–UER 56567. Due to the higher productivity and predominance of business wood in the structure, as well as the significant price of roundwood, the commercial effect of using durable species is 2.7–3.9 times greater than the effect obtained from harvesting wood in plantations from fast-growing species.

Table 2. Commercial efficiency of forestry measures for timber harvesting in 1 ha of protective forest stands on plakors and slopes of the forest steppe in the south of the Russian Plain.

Calculated Indicators	Windbreak Forest Strips on a Flat Type of Terrain		Runoff-Regulating Forest Strips on a Slope Type of Terrain	
The main forest-forming breed	Fast-growing precocious breeds	Slow-growing long-lasting breeds	Fast-growing precocious breeds	Slow-growing long-lasting breeds
	Hanging birch	Petiolate oak	Silver poplar	Siberian larch
Profit from the sale of business wood	EUR 14189	EUR 43784	EUR 10811	EUR 55135
Profit from the sale of biofuels	EUR 3784	EUR 2973	EUR 4865	EUR 2432
Total cash flow over the life of the forest plantation	EUR 17973	EUR 46757	EUR 15676	EUR 57567
Net profit from the sale of business wood	EUR 13804	EUR 43399	EUR 10310	EUR 54635
Net profit from the sale of biofuels	EUR 3399	EUR 2588	EUR 4364	EUR 1932
Total net cash flow over the life of the forest plantation	EUR 17203	EUR 45987	EUR 14675	EUR 56567

In the structure of net income from the sale of wood, the share of income received from the sale of biofuels in durable breeds is 4%–7%, in fast-growing breeds it increases to 22%–33%.

In general, the cost of harvesting wood reduces the commercial effect by 2%–7%.

3.2. Assessment of Forestry Efficiency of Land Use Equipped with a System of Protective Forest Stands (Per 1 ha of Agricultural Landscape)

3.2.1. Technological Parameters of the Placement of Protective Forest Stands within the Agricultural Landscape

When assessing the spatial impact of windbreak forest plantations on the adjacent territory, the schemes of typical land use located on the plains of the forest-steppe zone were studied. It was found that, in most cases, the plots have a rectangular shape with a size of 2000 m × 2000 m. According to the standard documents on the creation of forest

strips [31], which recommend inter-lane distances of 30 heights of trees (H), 5 forest strips with a total area of 9–12 hectares will be required for afforestation of these lands, depending on the tree species. The normative forest cover in this case is 2.3%–3.0%.

The stability of agriculture on flat lands is ensured by the convergence of distances between plantations from 30 H to 15–22 H, with a natural increase in the forest cover of occupied land use to 4.0%–5.4%. This leads to a decrease in wind speed within the agro-landscape by 25%–30% and brings its protection from natural anomalies to 100% [41].

The modeling of a stable forest-agrarian landscape on a convex catchment profile has established that in conditions of uneven relief, its protective forest cover increases with increasing slope steepness due to a decrease in inter-band distances. This is due to an increase in the erosion hazard of lands when there is a significant excess of the permissible amount of their flushing as a result of harmful runoff [42,43]. As on the plain, on the slopes, the productivity of the forest also varies in proportion to the protective forest cover of the territory.

3.2.2. Economic Assessment of the Productivity of Land Use Equipped with a System of Protective Forest Stands

Calculations show that in a flat area with a normative forest cover of 2.3%–3.0%, the unit productivity of stands that have reached the age of reforestation of plantations, with a value of 9.7–14.9 m^3 per hectare of land use, will be provided. At the same time, the systems of protective forest plantations with typical bioengineering parameters that have entered the operational age will allow to receive net income from the sale of wood products obtained as a result of repeated afforestation and selective sanitary logging in the amount of EUR 396–EUR 1423 (Table 3). An increase in the level of forest cover of the landscape increases this effect by 1.2–1.8 times (r^2 = 99%) compared to its typical parameters.

Table 3. Bioengineering models of forest-reclaimed land use on flat terrain type (based on 400 hectares of land use).

Calculated Indicators	"Windbreak" Forest Reclamation Strategy 1		"Windbreak" Forest Reclamation Strategy 2		"Windbreak" Forest Reclamation Strategy 3	
The range of influence of trees, H	30		22		15	
Forest stand-to-forest stand space, meters	600		400		270	
The main forest- forming breed	1	2	1	2	1	2
Number of forest belts, pieces	5		6		9	
Total area of forest belts, ha	9.0	12.0	10.8	14.4	16.2	21,6
Total land use area, ha	391.0	388.0	389.0	386.0	384.0	378.0
Protective forest cover,%	2.3	3.0	2.7	3.6	4.0	5.4
Unit (per 1 ha of land use) productivity of forest belts, m^3	9.7	14.9	11.7	17.9	17.7	27.4
Unit net profit from the sale of wood products	EUR 396	EUR 1423	EUR 477	EUR 1716	EUR 726	EUR 2628
Unit average annual effect from the sale of business wood and biofuels, taking into account the time factor and the growth dynamics of the main breed (r = 2%)	EUR 166	EUR 427	EUR 200	EUR 515	EUR 305	EUR 789

Note: 1—Hanging birch and 2—Petiolate oak.

With an increase in the slope steepness from 2.1° (lightly washed soils) to 5.0° (medium-washed soils), the protective forest cover increases by 1.4–1.9 times (r^2 = 98%). In the same proportion, the unit productivity of the agroforestry landscape and the commercial effect of the sale of wood increases, respectively, from 12.2–15.7 to 23.4–30.3 m^3 and from EUR 435–EUR 1676 to EUR 839–EUR 3232 (Table 4). On steep slopes, sustainable land-use implies the use of the simplest hydraulic structures with a reduction in the width of forest strips from 3 to 2 rows. This leads to a natural decrease in the commercial effect of wood harvesting (about 24%), but it is not considered as a factor in reducing the effectiveness of forest reclamation in general.

Table 4. Bioengineering models of forest-reclaimed land use on a convex catchment profile (calculated per 1000 m in length).

Calculated Indicators	"Runoff-Regulating" Forest Reclamation Strategies							
Slope steepness	2.1–3.0°		3.1–4.0°		4.1–5.0°		5.1–6.0°	
Erosion hazard	Low-intensity erosion		Medium-intensity erosion				High-intensity erosion	
Initial state of soil fertility	Lightly washed		Medium washed				Strongly washed	
Forest stand-to-forest stand space, meters	270		190		140		130	
The main forest-forming breed	1	2	1	2	1	2	1	2
Total area of forest belts, ha	0.8		0.8				0.6 *	
Total land use area, ha	27.0		19.0		14.0		13.0	
Protective forest cover,%	3.0		4.2		5.7		4.6	
Unit (per 1 ha of land use) productivity of forest belts, m^3	12.2	15.7	17.3	22.3	23.4	30.3	18.9	24.5
Unit net profit from the sale of wood products	EUR 435	EUR 1676	EUR 618	EUR 2381	EUR 839	EUR 3232	EUR 677	EUR 2611
Unit average annual effect from the sale of business wood and biofuels, taking into account the time factor and the growth dynamics of the main breed (r = 2%)	EUR 282	EUR 503	EUR 401	EUR 715	EUR 545	EUR 970	EUR 439	EUR 783

Note: 1—Silver poplar and 2—Siberian larch; *—with a mandatory device in the lower aisle of the simplest hydraulic structure (shaft–ditch).

The average annual expression of net income from the sale of wood varies over time —from a negative value, starting with the year of planting of forest plantations, to a positive and increasing value—in subsequent years before reforestation. In this regard, the average annual (discounted) net income will depend on the period of tree-crowns. Despite the fact that fast-growing breeds are characterized by an earlier period of crown closure (by about 40%) than slow-growing durable breeds, due to higher quality wood and a significant market price for 1 cubic meter of round wood, the use of Petiolate oak is more than 2.5 times more profitable on an average annual basis than the use of Hanging birch, and the use of larch is 2.0 times more profitable than the use of poplar. This confirms the prospects of using long-lasting forest-forming species for afforestation of the flat lands of the forest-steppe of the south of the Russian Plain.

It should be noted that this trend has been observed in Russia for the last two years, during which time, as a result of the pandemic, there was a sharp increase in demand and prices for valuable wood in the construction market [44].

4. Discussion

Global climate change and energy security are two key issues that are currently the subject of environmental discussions around the world. Despite the fact that these are completely different and unique problems, they are inextricably linked. It is noted that agroforestry can affect CO_2 levels not only due to carbon uptake, but also due to the substitution of fossil fuels by the biomass produced [45]. However, the economics of supplying wood biomass from the agroforestry system to the consumer is a difficult task [46].

We assumed that sustainable forest-reclaimed land use means providing forests with benefits for land users in the form of ecosystem goods and services in the long term. As for wood products, in order to determine the permissible annual level of wood harvesting, governments evaluate the supply of wood, which is expressed in its maximum volume in these forest conditions. Comparing the amount of wood actually harvested with the estimated wood reserves is one of the ways to track the management of forest-reclaimed land use.

Thus, the maximum supply of wood in the forest-steppe zone in the south of the Russian plain is 320–400 m^3 ha^{-1}, depending on the main forest-forming species. The increased

productivity of Siberian larch crops (400 m^3 ha^{-1}) is explained by several reasons and, in particular, the duration of growth during the growing season and regional environmental conditions conducive to tree growth [28].

In the estimates provided in the literature, it has been established that this volume of wood is adequate. Thus, the average density of plantings in European forests is 163 m^3 per ha. This indicator varies significantly in different countries, from 10 m^3 ha^{-1} in Iceland to 352 m^3 ha^{-1} in Switzerland [47]. The productivity of tropical plantations older than 30 years is 11.1–518 tons ha^{-1} [48].

Approximate estimates of the cost of wood are within a wide range. According to the latest forest resources assessment report published by the Food and Agriculture Organization of the United Nations [49], as of 2020, the selling price of wood in the supplies brought from Belarus is the minimum value—$37.93 per m^3, from Canada—$80.27, the maximum starting price is wood supplied from the United States ($207.23), Ireland ($226.96) and Serbia ($256.18).

Our estimates are based on the realizable price of wood products in the domestic market of Russia and these estimates do not contradict the available data—the cost of 1 m^3 of roundwood lies within EUR 72–EUR 143 (USD 81–USD 162), depending on the forest-forming breed, the cost of firewood is EUR 24 (USD 27).

On the Great plains of North America and in the Canadian prairies, protective forest structures are used to regulate wind and reduce soil erosion. This form of agroforestry has proven itself well and is accepted by farmers and politicians [50]. As for the technological aspects of forest plantations, it is reported that when placing windbreak forest strips, the optimal length of the inter-band cage should be approximately 10–12 times greater than the height. The standard density, as a rule, is approximately at least 2500 trees per hectare (that is, the trees are located at a distance of 2 m from each other). Other studies have noted that the wind pattern is influenced by trees at a distance of about 15 [41] and a tree height of 10 [51]. We also proceed from the fact that the protection of land tends to 100% with distances between trees of 15 heights.

Narrow, but strategically located runoff-regulating forest strips are very effective for improving field drainage and combating soil erosion. It has been found that in addition to increasing the structural stability of the soil, tree roots can enhance water penetration and improve water accumulation by increasing the number of soil pores. Tree roots and trunks also act as physical barriers to reduce surface water runoff [52].

Special studies conducted on a group of farms in Pont-bren (Wales, Great Britain) [53] showed that, within three years after planting on the slope of trees, water penetration rates improved by 60 times compared to the initial value. It has been proven that by increasing the permeability of the soil and the ability to retain water, trees reduce runoff. At the same time, it is noted that planting oak on the slopes should be avoided, as this reduces the ability of this crop to survive. Instead of oak, it is recommended to use hardy tree species on the slopes.

To maintain the forest plantations in a viable state, researchers recommend logging after 15–20 years as this will give the trees more space to grow. It will also increase wood yield in the long term with the simultaneous production of wood fuel harvest in the short term [51]. Available studies of deciduous plantings [54] show that the cost of manual care of young plantings in harsh conditions, depending on the size of the tree and the thickness of the stands, ranges from EUR 343 ha^{-1} to EUR 488 ha^{-1}. According to our calculations, measures for sanitary logging of care in plantings using carburetor chainsaws are cheaper—EUR 114–EUR 149, depending on the orography of the area. This is explained by the regional standards of costs for forestry care in Russia.

For the economic assessment of the productivity of agroforestry systems, as a rule, Land Equivalent Ratio (LER) is used. It is calculated as the ratio of the area required for monoculture to the area of agroforestry at the same management level to obtain a certain crop [55]. Based on the use of this indicator, it was found that the crop component provides a higher return compared to the negative return from the tree component in

agroforestry. This is due to the high cost of creating trees. Thus, the gross profit of agroforestry in Denmark was lower (EUR 112 $ha^{-1}year^{-1}$) compared to the United Kingdom (EUR 5083 $ha^{-1}year^{-1}$). At the same time, the gross profit from the tree component was, respectively, EUR-956 $ha^{-1}year^{-1}$ and EUR-567 $ha^{-1}year^{-1}$ [56].

In other studies devoted to the economic assessment of agroforestry productivity, the net present value (NPV) indicator is used [57]. It is noted that in Denmark, in comparison to other production systems, the NPV of the single component of the tree was the lowest, and was negative from 1 year with a value of EUR-931 ha^{-1} (1996) to 12 years with a value of EUR-121 ha^{-1} (2007). However, since year 13 (2008), the tree component has demonstrated a positive NPV of EUR309 ha^{-1} [58]. In our research, we also came to the conclusion that in the first years of planting life, the commercial effect of trees is negative. Therefore, the profit from harvesting wood from plantations that have reached the designed height is always lower on an annual average than its annual value.

Despite the fact that agroforestry is a very popular topic in the world, there is currently a stagnation of agroforestry in Russia. The main studies on the analysis of the effectiveness of protective forest plantations were mainly carried out in terms of a planned economy and have now lost their relevance [40]. The instructions and recommendations in force in the country on afforestation technologies of flat [31] and sloping [32] terrain are dated to the second half of the last century, which introduces some uncertainty, both for regional and global estimates of the supply of wood by protective plantings.

Nevertheless, the modern imperative of the Russian government, based on the transition to sustainable environmental management and a low-carbon economy, requires the establishment of the possible volume of wood stocks supply by agroforestry, which implies an assessment at the current prices of actual data on the productivity of forest plantations. Calculations show that 1 ha of forest-reclaimed land use within the accepted conditions in the forest-steppe can produce wood component products on average for a lifetime in the amount of EUR 166–EUR 970 $year^{-1}$, depending on the number of trees on the site. This is a worthy justification for encouraging farmers to integrate protective plantings into their agricultural systems in Russia.

A new trend of an increase in the value of long-lasting forest-forming species in agroforestry, compared with fast-growing precocious breeds due to extremely high market prices, has prevailed in domestic markets under the conditions of a pandemic [44], confirms the promising use of Petiolate oak for afforestation of plains and Siberian larch for afforestation of slopes in the forest-steppe zone in the south of the Russian plain.

5. Conclusions

Systems of windbreaking and runoff-regulating forest plantations contribute to solving problems of organizing rational nature management on flat and sloping lands. They help protect arable land from wind and water erosion, ensure the sustainability and safety of agriculture, and prevent emergencies. This study was conducted to evaluate the effectiveness of wood harvesting activities in agroforestry systems, based on modeling different tree placements from each other. The results of the study expand on the existing knowledge about tree productivity, logging costs and marginal commercial effects (net profit) from harvesting wood resources that can be obtained in the forest-steppe zone in the south of the Russian Plain. Based on the system analysis, the regularities of the dynamics of these indicators were obtained. It was found that on flat lands, wood productivity and the magnitude of the commercial effect of wood harvesting is strictly dependent on the selected level of protective forest cover and bioengineered features of forest plantations. On sloping lands, this effect is mainly due to the steepness of the slope and the degree of soil washout. At the same time, the complication of orographic conditions increases the cost of logging by a third. Until extensive research on this problem is developed, the presented research results can be recommended for use by scientific, design and production units of a vast region of Russia and adjacent regions with similar natural and climatic conditions. This information is necessary, at least, for an objective assessment of the importance of

agroforestry in the country in modern economic conditions. The study will justify the need for forest reclamation of flat and sloping lands, develop the most effective scenarios for their afforestation, pre-determine the volume of wood supply for each scenario, determine its commercial effect, and will also contribute to the introduction of environmentally safe and sustainable farming systems, for the conservation of Russian land-resources.

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