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Age periods of development of protective forest stands in the restoration of eroded ravine-gully lands

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Abstract. Currently, great attention is paid to the role, importance, optimal use of soils, their protection, and combating degradation. By adopting the Sustainable Development Goals at the national level, Ukraine is obliged to implement new programmes and projects that will guarantee macroeconomic stability, environmental balance, and social cohesion in practice. In the course of the studies of the multifunctional role of protective forest stands, which at one time were created in eroded territories, which include ravine-gully lands, to revive the properties of soils, a study was conducted to justify their restoration function. 90 soil and lysotypological points were laid in anti-erosion plantings of different periods of plant growth and development with the selection of 270 soil samples to fulfil this goal. Their water-physical and agrochemical properties were investigated with the processing of the obtained data by statistical methods. Based on the analysis of scientific literature sources, the examination of successful production experience and the conducted research of anti-erosion plantings to determine their impact on soil properties and the environment, qualitative stages of ecological restoration of eroded soils were developed. Changes in the age periods of growth and development of woody plants in protective forest stands created on ravine-gully lands lead to a gradual ecological restoration of eroded soils. A clear correlation between the age periods of growth and development of woody plants with qualitative stages of ecological restoration of eroded soils was obtained. The selection of research objects provided for considering the same technology for creating anti-erosion plantings, growth, and development in the same conditions, which would correspond to five age periods of growth and development of woody plants. In each age period, qualitative changes occur during the growth and development of vegetation cover, and quantitative changes in indicators that characterise the properties of the soil are presented in comparison with the control that was selected to be a pasture. The main functions of these plantings are given. All age periods of growth and development of anti-erosion plantings in terms of conducting forestry measures for the successful cultivation of anti-erosion plantings and their effective action were considered. The stages of ecological restoration of eroded territories are clearly coordinated with the selected age periods. Prospects for understanding the process of restoring protective vegetation cover, in particular, forest stands, and their direct impact on the properties of eroded soils open up

Keywords: erosion processes, eroded soils, anti-erosion role, development periods, qualitative stages, soil properties, hydraulic roughness

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Introduction

Currently, the role, importance, and optimal use of soils, their protection, and control of degradation are given great attention (Pdivinen et al.,1994; Manual on methods and criteria, 1994; Lund, 1998; ISO/TR 14061, 1998; Mayer, 2003; Johnson, 2004; Duran Zuazo & Pleguezuelo, 2008; Prescott, Katsensteiner & Weston, 2021). According to experts from international organisations, 47.5% of the Earth's land is degraded land. As of 2015, Ukraine had a total area of degraded land of 148.14 km^2 (25.57%). At the 2015 UN Summit on Sustainable Development, a common vision of new guidelines for the development of a planetary society until 2030 (Let's save the soil) was presented. Ukraine must implement new programmes and projects that in practice guarantee macroeconomic stability, environmental balance (On the National programme, 2000), and social cohesion to achieve Sustainable Development Goals at the national level. Thus, ensuring the rational use, protection, and improvement of the natural environment, in particular, the properties of eroded soils, is relevant.

Grandiose work on the creation of anti-erosion plantings in Ukraine was conducted in the 60s of the 20th century. A comprehensive study of their impact on the restoration of the properties of eroded ravine-gully lands began in 1980. According to the results of research work of the Department of Forests Restoration and Melioration of the National University of Life and Environmental Sciences of Ukraine, qualitative stages of ecological restoration of eroded territories were proposed to establish the sequence of elimination of the consequences of water erosion processes on ravine-gully lands (Maliuha, 1987, 2008). The ecological restoration was conducted through the use of anti-erosion forest stands.

The entire life cycle of forests consists of a consistent combination of certain phases of growth and development. Therewith, the temporary state of the forest is reflected in the corresponding stages. Thus, the phase of growth and development of forest crops is a certain qualitative and quantitative state during a certain period of life. N.P. Kobranov is rightly considered the founder of the theory of growth and development phases, and subsequent research in this area was continued by V.V. Ogievsky, A.A. Khirov, P.R. Talman, M.E. Tkachenko, P.V. Voropanov, L.N. Hribanov, V.G. Atrokhin, A.A. Kairukshtis, A.I. Yuodvalkis, and others (Merzlenko & Babich, 2020). Various interpretations were obtained, but the goal of all was to promote the implementation of economic measures necessary to optimise the growth of plantings (reforestation): the addition and evaluation of crops, the regulation of living conditions through the use of treatment logging, etc.

M.A. Lokhmatov (1985) considers such periods of development of protective forest stands on ravine-gully lands: 1 – formation, 2 – active development and interaction of tiers, 3 – relatively stable structure and mutual influence of storeys, 4 – weakening of vital activity of plantings, their ageing, degradation, and decay of stands in the context of assessing their condition (Lokhmatov, 1999). A similar distribution by stage of development is provided by (Johnson, 2004).

Recently, various researchers have paid a lot of attention to this issue (Duran Zuazo & Pleguezuelo, 2008; Prescott, Katsensteiner & Weston, 2021; Johnson, 2004; Yukhnovsky, Dudarets, Maliuha & Khryk, 2013). A study of certain aspects of land reclamation properties of the park stands in difficult terrain conditions was conducted (Minder, Maliuha & Yukhnovsky, 2019). Unfortunately, the studies of ravine-gully lands are insufficient.

The purpose of this study is to investigate the anti-erosion role of forest stands by their age periods of development in the conditions of ravine-gully lands. The eroded land consists of 4.5 million hectares with medium and heavily washed-out soils, in particular, 68 thousand hectares have completely lost the humus horizon. Prospects for understanding the process of restoring protective vegetation cover, in particular, forest stands, and their direct impact on the properties of eroded soils open up.

Materials and Methods

The main volume of research work has been conducted in the forest-steppe zone for ten years. The study was conducted on the territory of two former hydromeliorative forest stations – Kanivska (1958) and Rzhyshchivska (1964), created to eliminate the consequences of water erosion by hydraulic and forest reclamation methods in the protective zone of the Dnipro river. Protective forest stands on eroded ravine-gully lands were chosen as the objects of research.

The objects that had the same creation technology, grew and developed under the same conditions, and corresponded to five age periods of growth and development of woody plants were selected. The pasture was selected as the control.

90 soil lysotypological sites were laid with the selection of 270 soil samples by the selector (Maliuha, Dudarets, Yukhnovsky & Harkava, 2006; Maliuha et al., 2014).

Since the destruction of the soil occurs by concentrated surface runoff, indicators that characterise its structure, hardness, and water permeability were selected to assess changes in the anti-erosion properties. Structural analysis of the soil was determined by the Savvinov method

(Astapov, 1958) by dry sieving of a soil sample weighing up to 1.0 kg on a sieve column from 10 to 0.25 mm. The soil hardness was determined by the Golubev device in 30-fold repetition. The soil hardness M.A. Kaczynski scale was used (Berezhniak, 2013; Zrazhevsky & Lohvynenko, 1971). Determination of soil water permeability was conducted using steel cylinders with a diameter of 80 mm and a height of 100 mm, which are sharpened in the lower part for easy installation in the soil. The study was performed from the surface of a 10-centimetre layer of soil. The lower cylinders were half buried in the soil, and the upper 50 mm were filled with water. A column of water with a height of 50 mm conventionally corresponds to the water level during the passage of a heavy downpour. The stopwatch determined the time of water absorption in a 10-time repetition.

The assessment of changes in the fertility of eroded soils was conducted by agrochemical indicators of the 1 metre of soil. The content of agrochemical indicators was obtained by the following methods: easily hydrolysed nitrogen, mg/kg of soil – Tiurin-Kononova (Workshop on agrochemistry, 2001); mobile phosphorus and exchange potassium, mg/kg of soil – Kirsanov (Workshop on agrochemistry, 2001); humus, % – Tiurin (Workshop on agrochemistry, 2001). Based on the results obtained, considering the density of soil composition, nutrient reserves of a 1-meter thickness were calculated.

Statistical data processing was conducted using graphoanalytical, correlation, and regression analysis using the Excel and Statistica programmes.

Results and Discussion

Changes in the age periods of growth and development of woody plants in protective forest stands created on ravine-gully lands lead to a gradual ecological restoration of eroded soils, which is reflected in Table 1.

Table 1. Correlation of age periods of growth and development of woody plants with qualitative stages of ecological restoration of eroded soils

Age periods, years	Content of age periods of growth and development of woody plants of protective forest stands	Stages restoration	Content of qualitative stages ecological restoration eroded soils
up to 7	Engraftment and closure of forest crops	I	Beginning of impact on eroded soils, slowing down and sharply reducing erosion processes
8-15	Forming a forest tent of plantings	II	Stopping soil erosion, strengthening their biological processes
16-30	Intensive differentiation of woody plant species	III	Substantial improvement of the physical and chemical properties of soils, complete cessation of erosion processes
31-60	Formation of the forest biogeocenosis	IV	Ecological restoration of eroded growing conditions and creation of prerequisites for the return of such lands to economic circulation
Over 60	Effective action of the first generation of forest stands	V	Full return of land after rehabilitation to full-fledged economic circulation

In the first age period of life (up to 7 years of age), forest crops that are created on eroded lands take root. Success in the field of protective afforestation depends on the quality of implementation of the technology for creating forest reclamation stands.

In the first age period, protective forest stands do not show a statistically substantial effect on soil properties compared to the control (Table 2). During this period of growth and development of woody plants of anti-erosion plantings, there are representatives of living grass aboveground cover, mainly steppe or meadow species. On the one hand, herbaceous plants serve as important components of the natural protective vegetation cover, which counteract the intensive development of erosion processes, on the other hand, they create quite powerful competitive conditions for the engraftment of protective forest stands. Their number during this period is 100-300 pcs.*m^2.

Table 2. Indicators of restoration of properties of the upper 10-centimetre soil layer under the influence of forest stands and invertebrates

Plantings of up to 7 years of age	**Hardness, kg*cm^{-2}**	**Water permeability, mm*min^{-1}**	**Structural particles >1 mm, %**
	χ ± m		
Pure oak trees	19.3 ± 0.4	6.5 ± 0.4	27.8 ± 1.0
Control	20.4 ± 0.3	6.0 ± 0.5	24.5 ± 0.7
Mixed oak trees	19.1 ± 1.0	7.0 ± 0.7	32.1 ± 1.2
Control	20.1 ± 0.4	3.9 ± 0.4	28.6 ± 1.1
Pure pine trees	18.7 ± 1.2	6.5 ± 1.9	34.4 ± 3.6
Control	19.0 ± 0.6	6.3 ± 0.3	26.6 ± 0.6
Mixed pine trees	19.0 ± 0.4	5.6 ±0.9	31.0 ± 1.3
Control	20.5 ± 0.5	4.3 ± 0.4	25.8 ± 0.8

Among the representatives of grass vegetation that is intensively developing, it is necessary to name: field bindweed, narrow-leaved peas, noble yarrow, common sainfoin, chickweed, field clover, autumn hawkbit, woolly burdock, cypress spurge, common thistle, etc.

The conducted studies established that there is a certain improvement, and sometimes deterioration of some indicators that determine the properties of the soil, in particular, its hardness, structure, and water permeability. Indicators that characterise agrochemical properties, in particular, the content and reserves of nutrients, also do not have a statistically substantial difference, since their values differ slightly from the control ones. Nutrient reserves of a metre-deep soil layer are shown in Table 3.

Table 3. Nutrient reserves of a metre-deep soil layer

Plantings of up to 7 years of age	**Nutrient reserves**			
	organic matter, t*ha^{-1}	**easily hydrolysed nitrogen**	**mobile phosphorus**	**exchange rate potassium**
		kg*ha^{-1}		
	χ ± m			
Pure oak trees	75 ± 4.2	274 ± 22.0	354 ± 14.6	266 ± 16.0

Table 3. Continued

Plantings of up to 7 years of age	Nutrient reserves			
	organic matter, t*ha^{-1}	easily hydrolysed nitrogen	mobile phosphorus	exchange rate potassium
		kg*ha^{-1}		
	χ ± m			
Control	57 ± 3.5	201 ± 2.3	200 ± 17.0	239 ± 14.3
Mixed oak trees	77 ± 4.4	282 ± 13.8	348 ± 13.4	276 ± 15.5
Control	60 ± 8.8	213 ± 4.0	212 ± 4.6	238 ± 20.2
Pure pine trees	61 ± 6.1	204 ± 9.2	428 ± 13.6	585 ± 33.6
Control	68 ± 2.1	202 ± 7.5	418 ±13.5	508 ± 19.7
Mixed pine trees	74 ± 4.2	224 ± 9.4	458 ± 24.4	564 ± 20.5
Control	75 ± 3.1	197 ± 3.0	400 ± 10.4	507 ± 23.9

The relatively weak influence of forest stands on soil properties is explained by the fact that it is extremely difficult for them to adapt to uncharacteristic and harsh growing conditions, so they face high energy costs and a substantial indicator of the intensity of living space (Maliuha & Minder, 2020). The intensity of falling off depends mainly on compliance with the technology of creating plantings, and on how well it is possible to create conditions for the engraftment of plants that are sensitive at a young age and simultaneously plastic in terms of attachment.

Plantings need help in the form of timely agrotechnical care, which gives them the opportunity to get rid of excessive competition of grass vegetation, and it is easier to overcome "stressful" situations during engraftment. A characteristic feature of the first age period in anti-erosion terms is the fact that there is no unified layer of the forest floor. Optimal density of artificially created plantings can be adjusted for the duration of their rising period.

During the second age period of growth and development of woody plants (from 8 to 15 years), a forest tent is formed. There is a complete closure of branches in rows and aisles, the soil is covered with a unified layer of litter. Grassy vegetation from plantings of dense woody plant species, when the soil illumination is up to 10% compared to an open place on sunny days, is substantially limited or does not exist at all. It occurs only in places of a sparse wooden tent and on the edges in the amount of 0-15 pcs.*m^2, and in the plantings, there are only a few shade-tolerant representatives: meadow geranium, wood bluegrass, hairy sedge, narrow-leaved lungwort, hazelwort, ground elder, yellow archangel, etc.

Thus, as woody plants of protective forest stands grow and develop, due to the growth of crowns and shading of the soil, the grass cover changes. Light-demanding types of grass vegetation thin out and gradually disappear, being replaced by more adapted shade-tolerant ones.

The formation of a unified layer of litter, which limits the conditions for the intensive development of meadow grass vegetation, increases its hydraulic roughness, promotes the transfer of surface meltwater and stormwater to ground water, and preserves soil moisture. The moisture capacity of the undisturbed state of the forest floor, depending on the species composition of plantings, can reach 150-200%. Disruption of the litter condition due to the possible manifestation of surface runoff or herding of livestock substantially reduces its moisture capacity by 1.4-1.9 times. During this period, the interpenetration of root systems continues, and the development of deep soil horizons depending on the density and composition of plantings (Pasternak, Shinkarenko & Kravcova, 1974;

Orlovsky, Podzharov & Vorob'ev 1980; Maliuha, 1987; Minder, Maliuha & Yukhnovsky, 2019).

This age period is characterised by an increase in the number of soil invertebrates: worms, springtails, nematodes, and mites (Zonn, 1955; Zrazhevsky, 1957; Zrazhevsky & Lohvynenko, 1971; Gordienko, Nagornaya & Kisten', 1986), which, in addition to their main function, increase the water permeability of the soil. After litter transformation, their excrement accelerates bacterial activity (Kachinskij, 1975; Prescott, Katsensteiner & Weston, 2021). Earthworms play a special role in mixing and crushing litter with clay soil particles (Zrazhevskij, 1957; Zrazhevskyi & Lohvynenko, 1971; Kachinskij, 1975). Their excrement is much richer in phosphorus than soil: they contain 300% more lactate-soluble phosphoric acid and 40% more nitrogen. Earthworms need well-filled air and moist soil with *pH* 5.8-8.3. Due to the tunnels dug by worms, the soil loosens. Ants also substantially affect soil loosening and mixing (Zonn, 1955; Pogrebnyak, 1955; Zrazhevsky, 1957; Zrazhevsky & Lohvynenko, 1971).

The activity of invertebrates and other shrews has a positive effect on the physical and water-physical properties of the soil, which in turn causes changes in physico-chemical characteristics, helping to slow down the development of erosion. The properties of the soil, the main ones of which are determined by hardness, water permeability and structure, are peculiar markers of its anti-erosion capabilities (Table 4).

Table 4. Indicators of restoration of properties of the upper 10-centimeter soil layer under the influence of forest stands and invertebrates

Plantings aged 8-15 years	**Hardness, kg*cm^{-2}**	**Water permeability, mm*min^{-1}**	**Structural particles >1 mm, %**
	$\chi \pm m$		
Pure oak trees	16.7 ± 0.5	8.2 ± 0.4	32.9 ± 3.0
Control	19.8 ± 0.6	6.5 ± 0.6	25.1 ± 1.7
Mixed oak trees	17.2 ± 0.4	8.5 ± 0.2	38.4 ± 1.2
Control	19.5 ± 1.0	4.2 ± 0.7	29.0 ± 1.3
Pure pine trees	16.6 ± 0.6	7.3 ± 0.5	32.4 ± 2.6
Control	18.4 ± 0.9	6.5 ± 0.2	27.2 ± 0.9
Mixed pine trees	15.9 ± 0.7	8.3 ± 0.8	37.0 ± 2.1
Control	19.3 ± 0.8	5.0 ± 0.5	26.7 ± 1.1

In the second age period of growth and development of woody plants of forest reclamation plantings, the soil hardness decreases markedly by 10-18% compared to the control areas, which contributes to increased growth of root systems. Water permeability, having an inverse relationship with soil hardness, on the contrary, increases from 26 to almost 123%. The soil acquires structural features, in particular, the number of structural particles with a diameter of more than 1 mm increases by 19-38%. Admittedly, all these changes occur depending on the species composition of plantings.

Improvements in physical and water-physical properties, in turn, cause changes in the agrochemical characteristics of the soil. Freshly formed humus, holding soil lumps together and forming a water-resistant structure, not only slows down the development of erosion but also stops its manifestation. Reserves of the main agrochemical indicators of the metre-deep soil layer are shown in Table 5.

Table 5. Nutrient reserves of a metre-deep soil layer

Plantings aged 8-15 years	Nutrient reserves			
	organic matter, t^*ha^{-1}	easily hydrolysed nitrogen	mobile phosphorus	exchange rate potassium
		kg^*ha^{-1}		
	$\chi \pm m$			
Pure oak trees	90 ± 6.2	339 ± 28.9	460 ± 25.5	356 ± 27.8
Control	60 ± 6.4	207 ± 2.0	205 ± 12.2	241 ± 10.9
Mixed oak trees	103 ± 7.3	362 ± 23.8	456 ± 14.0	362 ± 12.5
Control	65 ± 7.0	218 ± 3.6	217 ± 10.3	245 ± 15.7
Pure pine trees	76 ± 2.0	235 ± 2.3	473 ± 5.6	645 ± 12.2
Control	70 ± 5.5	206 ± 7.0	400 ± 14.0	506 ± 16.1
Mixed pine trees	80 ± 2.6	246 ± 10.2	487 ± 15.2	624 ± 12.8
Control	74 ± 4.3	200 ± 4.1	407 ± 11.3	508 ± 20.2

Studies showed that in the second age period of growth and development of woody plants of forest reclamation stands, their influence increases. Reserves of organic matter increase by 8-58%, easily hydrolysed nitrogen – by 14-64%, mobile phosphorus – by 18-124%, exchange potassium – by 23-48%, depending on the type of plants and the composition of plantings.

The period of individual plant growth gradually turns into direct interaction and mutual influence. Plants begin to crowd each other in space, competing for light, water, soil nutrients, etc. The struggle for living space (Maliuha & Minder, 2020) is intensifying towards the end of the second age period in both the aboveground and underground parts of plantings. The tent of the stand becomes denser and more powerful along the entire height of the crown placement. Relations between woody plants become strained, which leads to the inevitable differentiation of primarily relatively fast-growing woody plant species.

Treatment logging in anti-erosion plantings should be aimed at improving the growth conditions of plantings (primarily the main types of woody plants), strengthening their reclamation functions, and increasing the level of biological resistance. Felling residues should be crushed and used as mulch to increase the anti-erosion role of plantings, (Lokhmatov, 1999).

Strengthening the reclamation functions of anti-erosion plantings is achieved by forming a well-developed shrub undergrowth and a tree tent; solid, sufficiently powerful, loose litter, which together increases the hydraulic roughness (Orlovsky, Podzharov & Vorob'ev, 1980; Teleshek, Cherneckij, Ivashko, 1985). Inspection logging, as noted by P.S. Pasternak, I.B. Shinkarenko, P.S. Kravcova, has a positive effect on improving soil development, increasing the volume of soil permeated with roots (Pasternak, Shinkarenko & Kravcova, 1974). Typical under such conditions is the cessation of the development of erosion processes in the territory occupied by the plantation and the suspension in the adjacent area. The threat of restoration of planar erosion remains in cases of transit surface runoff through micro-cavities.

In the third age period, there is an intensive differentiation of woody plants of artificial forest stands (16-30 years), and the formation of a forest environment in them in harsh conditions of competition for existence. Plants grow and develop due to the action of their active surface, which requires space, which is necessary to increase the size of the aboveground part of trunks and crowns, and spread root systems. Therefore, solving the spatial problem for individual trees and plantings, in general, is vital (Maliuha & Minder, 2020). During this age period, all trees cannot continue to grow and develop under the same conditions. The differentiation of trees, which manifests itself through intense competition for living space, becomes ineviTable There are processes of intensive thinning out of plantings, which negatively affect the anti-erosion properties, in particular, hydraulic roughness, which is partially compensated by the restoration of the activity of living subsurface cover. Grassy vegetation is 15-35 pcs.*m^2.

Among the representatives of the living ground cover during this age period of plantings, the following predominate: common bracken, unspotted lungwort, sweet woodruff, lanceolate star, Solomon's seal, wood avens, etc. that are common in fresh conditions of oak forests. In other forest-growing conditions, appropriate indicators are formed from representatives of the living subsurface cover.

During the third age period of ecological restoration of eroded land, plantings have a more intense impact on the environment and, especially, on the soil. Due to their forest reclamation properties, the following processes occur: the development of deep horizons by root systems, the death and restoration of active roots, accompanied by an increase in the content of organic matter in the soil; the accumulation of organic sediment on the surface, which, due to mineralisation, replenishes the soil with nutrients that are easily accessible to plants, and the manifestation of colmative ability by plantings. During this period, soil invertebrates become especially active, which, together with other representatives of flora and fauna, act as direct participants in soil-forming processes.

Indicators of physical, water-physical, physico-chemical, agrochemical, and biological properties of soils of this age period acquire specific statistical importance, which indicates their active soil-forming role. Improving the water-physical properties of the soil, primarily water permeability, contributes to the most complete transfer of meltwater and rainwater to intra-soil (Table 6). The soil hardness under pure and mixed plantings is 14.0-15.7 kg*cm^{-2}. Compared to the control, the decrease occurred by 13-26%. These are small values for the mentioned age period, which have substantially decreased compared to previous periods. Water permeability increased by 36-115%, and the content of structural particles increased by 64-102%.

Consequently, a substantial change in the water-physical properties of the soil causes the complete cessation of the development of erosion processes in the areas under forest reclamation plantings.

Table 6. Indicators of restoration of properties of the upper 10-centimeter soil layer under the influence of forest stands and invertebrates

Plantings aged 16-30 years	Hardness, kg*cm^{-2}	Water permeability, mm*min^{-1}	Structural particles >1 mm, %
	$\chi \pm m$		
Pure oak trees	14.0 ± 2.3	12.8 ± 0.9	52.6 ± 5.2
Control	19.0 ± 1.1	7.0 ± 0.8	26.0 ± 1.2
Mixed oak trees	14.9 ± 0.7	11.4 ± 0.3	53.9 ± 6.1
Control	18.9 ± 1.3	5.3 ± 1.0	30.1 ± 1.4
Pure pine trees	15.7 ± 0.6	9.4 ± 0.8	46.2 ± 2.5
Control	18.0 ± 0.7	6.9 ± 0.9	29.3 ± 1.7
Mixed pine trees	14.0 ± 0.5	10.3 ± 0.4	46.8 ± 1.8
Control	18.8 ± 0.8	5.8 ± 1.2	28.4 ± 1.3

Plantings begin to enter the fruiting phase, which has a positive result in the formation of self-seeding on open ravine slopes devoid of woody vegetation, which is important in anti-erosion terms. A comparison of the nutrient reserves of the specified age period is given in Table 7.

Reserves of organic matter increase by 22-51%, easily hydrolysed nitrogen – by 31-135%, mobile phosphorus – by 5-136%, exchange potassium – by 42-68%, depending on the type of plants and the composition of plantings.

During this age period, it is necessary to conduct treatment logging, which has an exclusively differentiated approach to each individual forest stand, depending on the characteristics of the growth and development of woody plants.

Table 7. Nutrient reserves of a metre-deep soil layer

Plantings of age 16-30 years old	**Nutrient reserves**			
	organic matter, t*ha^{-1}	**easily hydrolysed nitrogen**	**mobile phosphorus**	**exchange rate potassium**
		kg*ha^{-1}		
	$\chi \pm m$			
Pure oak trees	103 ± 4.9	416 ± 31.6	502 ± 19.4	421 ± 12.4
Control	68 ± 3.3	209 ± 3.0	213 ± 8.9	250 ± 17.1
mixed oak trees	104 ± 13.0	519 ± 35.3	430 ± 15.2	411 ± 67.8
Control	70 ± 9.2	221 ± 6.2	230 ± 10.7	249 ± 18.0
Pure pine trees	93 ± 3.5	272 ± 9.0	440 ± 42.0	727 ± 31.9
Control	75 ± 5.1	208 ± 7.3	420 ±13.7	512 ± 20.7
Mixed pine trees	98 ± 8.9	352 ± 46.4	578 ± 35.3	765 ± 25.3
Control	80 ± 5.8	204 ± 5.6	414 ± 12.4	514 ± 21.4

Notably, in protective anti-erosion plantings (especially under the age of 30), treatment logging should be performed with less intensity than in operational forests. It is advisable to chop the felled plant mass and spread it evenly over the territory. This measure aims to increase the hydraulic roughness of the surface, prevent possible washouts and erosion of the soil due to heavy rains and transit flow of surface runoff through micro-cavities.

Fourth age period, the life interval of which covers from 31 to 60 years is primarily characterised by the completion of the formation of the forest environment in forest stands involving fast-growing plant species and the manifestation of the effective action of their first generation. Scots pine and Scots oak, as representatives of long-lasting main plant species, have time to identify these functions only at the end of the mentioned period of development of forest stands. Successfully created protective forest stands of the first generation using fast-growing plant species in the presence of vital energy resources do not limit their existence at the age of 60 years. The formation of the forest environment radically changes the forest conditions in comparison with areas that are not covered with forest vegetation.

Anti-erosion plantings of this age period are characterised by the beginning of thinning out of the tent by reducing the number of leaves and needles per unit length of the shoot, and by conducting treatment cuts, removing stunted and dry trees. Care for such plantings is planned by the forester.

Because of this, the amount of organic precipitation decreases, the illumination of the soil increases, which together leads to intensive growth of grass vegetation (35-50 pcs.*m^2). The consequence of this is the appearance under the tent of oak stands, in addition to the wood bluegrass and hairy sedge, also hazelwort, sweet woodruff, ground elder; in robiniaceae – greater celandine; in pine – stoloniferous pussytoes, rare spring sedge, sheep fescue, etc. The root system of plants of this period develops the upper soil horizons more intensively, which has a positive effect on water permeability, and therefore contributes to the transfer of surface runoff to soil.

In this age period, the intensive influence of plantings on the properties of the soil and its soil formation continues. In terms of its properties, the soil becomes forest type and has substantial differences from agricultural soil.

Relative to the average indicators of physical, water-physical, physico-chemical, and biological properties of the soil, there is a statistically substantial difference not only in comparison with the control area, but also with previous age periods of growth and development of woody plants of forest reclamation stands. There is no surface runoff in forest areas. The investigated indicators of restoration of the properties of the active surface layer of the soil are given in Table 8.

Table 8. Indicators of restoration of properties of the upper 10-centimeter soil layer under the influence of forest stands and invertebrates

Plantings aged 31-60 years	**Hardness, kg*cm^{-2}**	**Water permeability, mm*min^{-1}**	**Structural particles >1 mm, %**
	$\chi \pm m$		
Pure oak trees	14.5 ± 0.6	20.0 ± 2.9	66.2 ± 1.6
Control	18.7 ± 0.9	7.4 ± 0.7	26.9 ± 1.7
Mixed oak trees	13.5 ± 1.0	14.2 ± 1.1	63.4 ± 3.2
Control	18.5 ± 0.8	6.8 ± 0.5	30.7 ± 2.0
Pure pine trees	15.4 ± 0.2	12.8 ± 0.4	56.2 ± 5.4
Control	17.6 ± 0.7	7.1 ± 0.8	31.3 ± 1.9
Mixed pine trees	13.3 ± 0.6	15.1 ± 0.2	58.6 ± 3.3
Control	18.2 ± 1.1	6.2 ± 0.9	29.8 ± 2.1

Soil hardness decreases by 12-27%, water permeability increases by 80-170%, the number of structural particles in the soil increases by 79-146% compared to the control indicators, depending on the plant species and the composition of stands.

Plantings continue to bear fruit en masse, which serves as the basis for the spread of seeds and the appearance of self-seeding. Its viability has features of manifestation not only in the areas of ravine slopes that remained uninhabited, but also under the tent or on the edge of anti-erosion plantings that continued to thin out due to the differentiation of stands.

Agrochemical properties, in particular, those presented here on the example of soil nutrient reserves, also have convincing statistical importance in comparison with the control (Table 9).

Table 9. Nutrient reserves of a metre-deep soil layer

Plantings of age 31-60 years old	Nutrient reserves			
	organic matter, $t*ha^{-1}$	easily hydrolysed nitrogen	mobile phosphorus	exchange rate potassium
		$kg*ha^{-1}$		
	$\chi \pm m$			
Pure oak trees	105 ± 1.8	330 ± 7.9	603 ± 25.1	884 ±40.0
Control	69 ± 4.5	217 ± 7.8	422 ± 14.7	518 ± 18.6
Mixed oak trees	106 ± 2.9	438 ± 45.7	619 ± 43.0	908 ± 27.0
Control	78 ± 8.1	219 ± 5.0	430 ± 11.3	520 ± 22.4
Pure pine trees	97 ± 10.6	426 ± 38.3	439 ± 10.9	401 ± 65.5
Control	67 ± 5.4	220 ± 6.3	217 ± 15.0	257 ± 19.3
Mixed pine trees	113 ± 3.2	499 ± 29.7	527 ± 16.4	452 ± 55.0
Control	65 ± 8.6	215 ± 8.2	221 ± 13.6	268 ± 23.2

Reserves of organic matter increase by 36-74%, easily hydrolysed nitrogen – by 52-132%, mobile phosphorus – by 43-138%, exchange potassium – by 56-75%, depending on the type of plants and the composition of plantings.

Therefore, the fourth age period can be characterised as the period of the beginning of the age of protective ripeness of anti-erosion forest stands on eroded lands (Pavlovsky, 1973). During this age period, natural reforestation extends to nearby agricultural land.

During this period of growth and development of woody plants of anti-erosion plantings, forest floor reserves range from 2.5 to 8.5 t/ha^{-1} (Yukhnovskyi, Dudarets, Maliuha & Khryk, 2013; Maliuha et al., 2021). Features of the influence of forest litter are as follows: reducing the physical evaporation of moisture from the soil, its compaction and freezing; promoting the accumulation of moisture due to meltwater and precipitation, which seep into the soil, and increasing the level of moisture capacity of the litter, which can reach 300-400%. There is an increase in the anti-erosion effect of protective forest stands not only on the territories that they actually cover but also on adjacent ones.

The fifth age period of effective operation of the first generation, characterised by the entry of middle-aged plantings into the self-regulation phase, is associated with an age interval of more than 60 years for woody plant species of a long life cycle. Forest stands involving Scots pine and Scots Oak during this period of their growth and development have a well-formed effective forest environment, in which forest conditions radically change in comparison with eroded territories that are not covered with forest vegetation.

The main indicators of restoration of physical and water-physical properties of the active soil layer of anti-erosion plantings are given in Table 10.

Table 10. Indicators of restoration of properties of the upper 10-centimetre soil layer under the influence of forest stands and invertebrates

Plantings older than 60 years	Hardness, kg*cm^{-2}	Water permeability, mm*min^{-1}	Structural particles >1 mm, %
	χ ± m		
Pure oak trees	13.9 ± 0.4	26.2 ± 0.7	65.3 ± 4.1
Control	18.9 ± 1.3	7.7 ± 1.1	28.7 ± 2.5
Mixed oak trees	13.2 ± 1.1	27.5 ± 0.3	77.1 ± 2.0
Control	18.6 ± 1.2	7.4 ± 0.7	32.5 ± 1.8
Pure pine trees	13.8 ± 0.5	21.7 ± 0.9	62.6 ± 1.0
Control	17.9 ± 1.0	6.9 ± 0.6	33.0 ± 2.4
Mixed pine trees	14.2 ± 0.3	26.0 ±0.5	68.3 ± 1.5
Control	18.0 ± 1.4	6.5 ± 0.8	33.7 ± 1.7

The soil hardness in mixed oak stands is the lowest – 13.2 kg*cm^{-2}. The overall soil hardness index of oak and pine stands decreased by 21-29% compared to the control. The value of the water permeability indicator increased by 214-300%. Mixed oak stands have the highest water permeability index – 27.5 mm*min^{-1}.

Such results correspond, according to the assessment by N.A. Kachinskij, to water permeability (Kachinskij, 1975; Berezhniak, 2013) for the first hour of seeping, which will be equal to more than 1000 mm. This is explained by the action of soil animals: moles, worms, and many other smaller ones, and the influence of root systems. Soil with such indicators is able to absorb even the transit part of surface runoff, which can enter plantings from the catchment area. It is important to consider positive changes regarding the increase in the share of structural aggregates by 90-137%.

The processes of soil formation in anti-erosion plantings continue to acquire intense manifestation, and the average values of the considered indicators of soil properties, as in the previous age period, have a statistically substantial difference not only in comparison with the control area but also with plantings of other age periods of growth and development of woody plants.

Under the tent of thinning out plantings, a sufficient amount of organic precipitation and optimal illumination determines the development of grass vegetation (50-150 pcs.*m^2). Its composition includes both shade-tolerant species – hazelwort, lanceolate star, male fern, hazelwort, unspotted lungwort, Solomon's seal, and relatively light-demanding – wood anemone, viola mirabilis, ribwort plantain, common dandelion, white clover, danewort, brown knapweed, red dead-nettle. Not only do self-seeding plants appear, but also undergrowth develops, increasing hydraulic roughness.

The properties of the forest soil continue to improve. Therewith, during this period (at least until the age of 70-80 years), the first generation does not manage to fully reach the level of properties of zonal soils that are formed under natural forest stands. A comparison of nutrient reserves of a metre-deep soil thickness under forest stands is given in Table 11.

Table 11. Nutrient reserves of a metre-deep soil layer

Plantings older than 60 years	Nutrient reserves			
	organic matter, t*ha^{-1}	easily hydrolysed nitrogen	mobile phosphorus	exchange rate potassium
		kg*ha^{-1}		
	$\chi \pm m$			
Pure oak trees	121 ± 14.3	440 ± 15.7	798 ± 34.1	1007 ±18.8
Control	71 ± 7.2	224 ± 6.3	423 ±17.2	523 ± 17.9
Mixed oak trees	146 ±3.8	417 ± 4.0	908 ± 23.6	1092 ± 30.7
Control	78 ± 5.2	230 ± 6.5	437 ± 16.2	527 ± 21.9
Pure pine trees	115 ± 2.7	494 ± 26.6	545 ± 12.0	497 ± 53.8
Control	83 ± 6.0	228 ± 9.2	237 ± 13.8	261 ±24.3
Mixed pine trees	128 ± 4.6	612 ± 18.4	732 ± 20.7	632 ± 42.9
Control	85 ± 9.0	240 ± 8.7	260 ± 14.3	268 ± 20.6

Reserves of organic matter increase by 38-87%, easily hydrolysed nitrogen – by 81-155%, mobile phosphorus – by 89-182%, exchange potassium – by 90-136%, depending on the type of plants and the composition of plantings.

Plantings continue to bear fruit, and the viability of self-seeding plants and their biological stability increase. Thus, after 60 years, protective anti-erosion plantings are defined as self-regulating ecological systems, that is, there is an ecological restoration of former eroded lands, and their transformation into productive, important territories for economic use.

This age period is characterised by the maximum manifestation of all functions of protective forest stands: energy, water-regulating, water-absorbing, soil-protecting, colmatative, soil-forming, restorative, recreational, sanitary-hygienic, aesthetic, educational, climate-regulating, environmental-stabilising. These functions work simultaneously and provide a multifunctional role for forest stands (Yukhnovsky, Dudarets, Maliuha & Khryk, 2013).

The maximum manifestation of all the above functions takes place only during the life of the forest or anti-erosion plantings as a powerful and well-established organism that acts clearly.

Conclusions

A clear correlation between the age periods of growth and development of woody plants with qualitative stages of ecological restoration of eroded soils was obtained. In each age period, qualitative changes occur during the growth and development of vegetation cover, and quantitative changes in indicators that characterise the properties of the soil, compared to the control (pasture).

In the first age period, protective forest stands do not show a statistically substantial effect on soil properties compared to the control. They need help in the form of timely agricultural treatment. If the plantings are successfully created, they do not need forestry care.

The second period is characterised by an improvement in physical and water-physical properties, which cause changes in the agrochemical characteristics of the soil. Forestry care is used if there were miscalculations in the selection of woody plant species or for non-compliance with the technology. For this purpose, lighting is conducted to improve growth conditions, strengthen land reclamation functions, and increase the stability of plantings. Felling residues should be crushed and used as mulch to enhance the anti-erosion role of plantings.

In the third period, there is a substantial change in the water-physical properties of the soil, which causes the complete cessation of the development of erosion processes in the areas under forest reclamation plantings. Treatment logging has an exceptionally differentiated approach, and it is advisable to grind the felled plant mass and spread it evenly over the territory to increase hydraulic roughness in regulating surface runoff.

The fourth period is characterised by the beginning of the age of protective ripeness of anti-erosion forest stands. There is an increase in their influence on the processes of soil formation. The average indicators of physical, water-physical, physico-chemical, agrochemical, and biological properties of the soil have a statistically substantial difference not only in comparison with the control area but also with plantings of other age periods of growth and development of woody plants.

After 60 years, as for the fifth age period, protective anti-erosion plantings are defined as self-regulating ecological systems that are characterised by the manifestation of basic functions.

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Вікові періоди розвитку захисних лісових насаджень у відновленні еродованих яружно-балкових земель

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Анотація. На теперішній час питанням ролі, значущості, оптимального використання ґрунтів, їхньої охорони та боротьби з деградацією приділяють величезну увагу. Ухвалюючи Цілі Сталого Розвитку на національному рівні, Україна зобов'язана впроваджувати нові програми та проекти, які на практиці гарантуватимуть макроекономічну стабільність, екологічний баланс і соціальну згуртованість. Під час наукових досліджень багатофункціональної ролі захисних лісових насаджень, які свого часу створювали на еродованих територіях, до складу яких входять яружно-балкові землі, для відродження властивостей ґрунтів проведено дослідження з обґрунтування їхньої відновлювальної функції. Для виконання поставленої мети закладено 90 ґрунтолісотипологічних пунктів у протиерозійних насадженнях різних періодів росту і розвитку рослин із відбором 270 зразків ґрунту. Здійснено дослідження їхніх водно-фізичних і агрохімічних властивостей із обробленням отриманих даних статистичними методами. На підставі аналізу наукових літературних джерел, вивчення успішного виробничого досвіду та власних досліджень протиерозійних насаджень із визначення їхнього впливу на властивості ґрунту і навколишнє середовище, розроблено якісні етапи екологічного відновлення еродованих ґрунтів. Зміна вікових періодів росту і розвитку деревних рослин у захисних лісових насадженнях, створених на яружно-балкових землях, призводить до поступового поетапного екологічного відновлення еродованих ґрунтів. Отримано чітке співвідношення вікових періодів росту і розвитку деревних рослин з якісними етапами екологічного відновлення еродованих ґрунтів. Добір об'єктів досліджень передбачав урахування однакової технології створення протиерозійних насаджень, зростання і розвиток в однакових умовах, які б відповідали п'ятьом віковим періодам росту і розвитку деревних рослин. У кожному віковому періоді відбуваються якісні зміни під час росту і розвитку рослинного покриву, а також кількісні зміни показників, що характеризують властивості ґрунту, які представлені порівняно з контролем, яким обрано вигін. Надано основні функції цих насаджень. Приділено увагу всім віковим періодам росту і розвитку протиерозійних насаджень у частині проведення лісівничих заходів для успішного вирощування протиерозійних насаджень та їхньої ефективної дії. З виділеними віковими періодами чітко узгоджуються етапи екологічного відновлення еродованих територій. Відкриваються перспективи розуміння процесу відновлення захисного рослинного покриву, зокрема лісових насаджень і їхнього безпосереднього впливу на властивості еродованих ґрунтів

Ключові слова: ерозійні процеси, еродовані ґрунти, протиерозійна роль, періоди розвитку, якісні етапи, властивості ґрунту, гідравлічна шорсткість