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Study of agroforestry methods and techniques for soil erosion prevention on agricultural land

Talgarbek Yzakanov*

PhD in Agricultural Sciences, Associate Professor
Kyrgyz National Agrarian University named after K.I. Skryabin
720005, 68 Mederov Str., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0003-3244-1663

Sovetbek Mamytkanov

PhD in Agricultural Sciences, Associate Professor
Kyrgyz National Agrarian University named after K.I. Skryabin
720005, 68 Mederov Str., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0002-4322-8377

Zhazgul Ibraimova

Postgraduate Student
Kyrgyz National Agrarian University named after K.I. Skryabin
720005, 68 Mederov Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0002-0141-0127

Elina Steinberg

Postgraduate Student
Kyrgyz National Agrarian University named after K.I. Skryabin
720005, 68 Mederov Str., Bishkek, Kyrgyz Republic
https://orcid.org/0000-0001-6842-4051

Cholpon Alibakieva

Postgraduate Student
Kyrgyz National Agrarian University named after K.I. Skryabin
720005, 68 Mederov Str., Bishkek, Kyrgyz Republic
https://orcid.org/0009-0009-9941-5508

Abstract. The study aimed to identify key factors and mechanisms for the improvement of soil and agroecosystem resilience by using agroforestry technologies in a changing climate. The impact of forest shelterbelts, crop mixing technologies and spatial planning techniques on restoring

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*Corresponding author

degraded lands and improving ecosystem functions was addressed. The research methodology was based on the synthesis and analysis of data from various scientific sources, and the use of theoretical models and field observations. Regions of Ethiopia, Kenya and Malawi were addressed in the analysis of the effects of multi-level forest belts and mixed crops on reducing erosion, improving soil structure and restoring biodiversity. The results of the study demonstrated that agroforestry interventions in these countries significantly reduced the intensity of water and wind erosion, improved soil water-holding capacity and restored the hydrological cycle. Forest belts increased moisture storage in arid regions of Ethiopia, improved crop yields by creating a favourable microclimate in Kenya, and protected rangeland ecosystems from degradation in Malawi. These interventions also increased soil organic carbon content, reducing the need for mineral fertilizers and minimizing anthropogenic impacts on the environment. The findings confirm the versatility of agroforestry approaches for land restoration and adaptation to climate change. The results demonstrated the importance of integrating agroforestry technologies into sustainable natural resource management systems, which emphasizes the need for scaling up in regions prone to land degradation, including the Kyrgyz Republic

Keywords: forest plantations; spatial planning; ecosystem services; land restoration; water balance management

Introduction

Agroforestry is one of the most promising technologies for sustainable land management and restoration of degraded ecosystems. Modern climate change, intensification of agricultural production and increased anthropogenic pressure on natural systems significantly increased soil erosion, which in turn has a negative impact on productivity and ecosystem functions.

The research relevance of the issue is determined by the global nature of the problem of land degradation, which affects both agricultural areas and natural ecosystems. Current trends in land use intensification, urbanisation and climate change substantially increased soil erosion, which negatively impacts soil productivity, environmental sustainability and the ability to support ecosystem functions (Kerimkhulle *et al*., 2023; Santosa *et al*., 2024). This creates serious environmental, social and economic risks.

Soil degradation is caused by a combination of natural and anthropogenic factors. Water erosion associated with intense precipitation and surface runoff leads to the loss of topsoil, which is rich in nutrients. Wind erosion, typical for steppe and arid regions, is exacerbated by the lack of vegetation cover, blowing away the fertile layer and deteriorating the soil structure. These processes not only reduce the agronomic value of soils but also exacerbate climate change through the release of carbon dioxide stored in the soil profile. Agroforestry is the subject of intensive research in scientific circles due to its significant role in protecting soil, restoring degraded land and increasing the sustainability of agroecosystems. A. Kaur *et al.* (2023) analysed the role of agroforestry systems in soil conservation and sustainable agricultural production. The study highlighted the employment of forest belts as the primary way to reduce soil loss and increase water retention capacity.

M.K. Jhariya *et al.* (2022) also addressed the management of soil organic carbon in agroforestry systems. They emphasised that the accumulation of organic carbon in the soil not only improves soil structure and fertility but also contributes to the restoration of degraded land. M.T.S. Budiastuti *et al.* (2021) studied agroforestry as a vegetation management strategy to combat forest degradation in Indonesia. This study highlighted that the integration of woody and herbaceous plants into forest ecosystems reduces erosion losses and helps stabilise ecosystem processes. B.C. Rodríguez *et al.* (2022) addressed the use of legumes in agroforestry systems. The study emphasises that such plants are central to strengthening the sustainability of soil systems.

D. Jinger *et al.* (2023) analysed the restoration of degraded land in India by introducing agroforestry. Furthermore, the authors emphasised that forest belts contribute to the restoration of biodiversity by providing habitat for different species of organisms. T.J. Sauer *et al.* (2021) analysed agroforestry practices for soil protection and sustainable agriculture. The study highlighted the significance of such systems for increasing the resilience of agricultural land to climate change. S. Kumar *et al.* (2024) considered agroforestry as a sustainable way to combat the climate crisis and increase the productivity of agricultural land. S. Kumar *et al.* highlighted that the integration of woody and shrubby plants into agricultural landscapes helps stabilise soils, improve water retention capacity and restore ecosystem services such as the hydrological cycle. Moreover, T. Plieninger *et al.* (2020) investigated the impact of agroforestry systems on sustainable landscape management. The study concluded that such systems help conserve biodiversity, improve ecosystem services and restore degraded lands. D.A. Martin *et al.* (2020) explored how land use history affects ecosystem services and the conservation value of tropical agroforestry systems. The study demonstrated that such systems have high potential to restore ecosystem functions, improve soil health and maintain natural balance in regions with intensive land use. M. Ghimire *et al.* (2024) reviewed agroforestry systems, addressing their role in improving food security and supporting rural livelihoods. The study confirmed that forest belts play a key role in protecting soil, restoring structure and increasing the productivity of agricultural systems.

The aim of this study was to analyse the potential of agroforestry systems in protecting soil, restoring degraded land and improving ecosystem functions. The objectives of the study were to analyse the effectiveness of forest shelterbelts and mixed crops in reducing soil erosion, to examine their role in restoring biodiversity and ecosystem services, and to evaluate spatial planning techniques for adapting agroforestry measures to different climatic conditions.

Materials and Methods

For this study, data for the year 2023 were analysed to incorporate current indicators of the effects of agroforestry on soil health in Ethiopia, Kenya and Malawi (Nkansah-Dwamena, 2023; Koné & Galiegue, 2023; Dagar *et al.*, 2024). This time interval was chosen to assess recent changes and the effectiveness of interventions in the short term. This time interval was chosen to analyse recent changes and assess the sustainability of the results in the relatively short term.

This study was based on the generalisation and analysis of existing scientific data related to agroforestry as an effective method of soil erosion control and restoration of ecosystem functions. The main objective was to systematise knowledge on the role of agroforestry in reducing land degradation, increasing soil productivity and strengthening ecosystem resilience. For this purpose, literature sources including research results, and data on the practical application of the methods were analysed (Kraft *et al.*, 2021; Singh & Singh, 2024).

Theoretical models based on digital elevation maps and climatic data were used to ensure the representativeness of the analyses (Amin *et al.*, 2023). Optimal forest strip patterns on slopes, hilly terrain and flat areas were investigated. Multilevel strips incorporating woody, shrub and herbaceous plants were studied, as well as crop mixing technologies aimed at enhancing the ecological functions of agroforestry systems.

An important part of the study was to investigate the environmental issues of land degradation. For this purpose, existing data on water and wind erosion, extent and impact on agricultural areas were analysed (Panagos *et al.*, 2021). A data systematisation method (Systematization of statistical data and…, 2022) was used for the study to analyse the main erosion factors such as intensive tillage, lack of vegetation cover and climate change. This approach provided an assessment of the potential of agroforestry in reducing soil degradation and greenhouse gas emissions by reducing organic carbon content.

A comparative analysis method was used for the study to compare data on the functions of forest shelterbelts from different sources and regions (Kaluza, 2023). This approach ensured the identification of patterns in the effectiveness of forest strips to prevent soil erosion, improve water balance and reduce wind speed. Comparison of the data assessed the versatility and adaptability of forest belts to different landscape and climatic conditions. To analyse the effectiveness of agroforestry measures, a modelling method (Vayansky & Kumar, 2020) was used to predict the effect of forest strips and crop mixing technologies on reducing erosion and restoring soil water balance. This method was used to study the long-term impact of agroforestry measures on agroecosystems under different natural and climatic conditions. To clarify theoretical data on the ecological benefits of agroforestry reclamation, the study used a field evaluation method (Field studies, 2024). This approach included observations and data collection in areas with field-protected forest strips in different natural-climatic zones. The field assessment allowed to study the impact of forest strips on soil moisture retention, stabilisation of groundwater table and reduction of dependence on artificial irrigation.

Soil moisture, surface runoff rate and vegetation condition were recorded during field studies. Observations were conducted both in arid regions, where special attention was paid to the ability of forest strips to reduce evaporation and increase soil water storage, and in zones with high erosion levels, where their role in protecting the fertile layer was assessed.

Results

The efficiency of agroforestry as an erosion control method. Scientific evidence confirms that the creation of shelterbelts improves soil physicochemical properties, including increased humus content, water retention capacity, and restoration of microbial activity (Kraft *et al.*, 2021; Singh & Singh, 2024). These changes help reduce greenhouse gas emissions by enhancing carbon storage in the soil profile (Yang *et al.*, 2024). An analysis of the literature has also shown that improving soil structure as a result of agroforestry activities has a positive impact on the restoration of ecosystem functions, such as regulating the hydrological cycle and increasing soil biological activity (Forest and landscape restoration and…, 2022; Shlapak & Zvorska, 2024).

The analysis of the data presented in Table 1 demonstrated a significant positive impact of agroforestry on key soil parameters in Ethiopia, Kenya and Malawi (Amin *et al.*, 2023). Before the introduction of agroforestry, the level of water erosion in these countries ranged from 16 to 18 tonnes per hectare per year, indicating a high degree of topsoil loss. After the measures, the values decreased to 5-7 t/ha per year, which indicated a 60-70% reduction in erosion. This reduction was attributed to the creation of forest belts that slowed down surface water runoff and improved soil structure.

Table 1. Efficiency of agroforestry as an erosion control method

Parameter	Ethiopia (before agroforestry)	Ethiopia (after agroforestry)	Kenya (before agroforestry)	Kenya (after agroforestry)	Malawi (before agroforestry)	Malawi (after agroforestry)
Level of water erosion (t/ha per year)	18	7	16	6	17	5
Organic carbon content (%)	1	1.8	1.1	1.9	1.2	2
CO_2 emissions (t/ha per year)	3	1.5	2.8	1.3	2.9	1.4
Water retention in the soil (mm per m^2)	110	150	115	158	112	160
Soil biological activity (soil health)	0.6	1.3	0.7	1.5	0.6	1.4

Source: compiled by the authors based on the Systematization of statistical data and the development and application of a methodology for assessing the impact of the use of the intellectual property system (2022), J.C. Dagar *et al*. (2024)

The organic carbon content of soils before the interventions was low, indicating land degradation. In Ethiopia, Kenya and Malawi, it was 1%, 1.1% and 1.2%, respectively. After the introduction of agroforestry measures, this figure increased to 1.8%, 1.9% and 2%. This increase of 50-67% is due to the accumulation of organic matter, which has restored soil fertility and improved carbon storage properties.

Before the measures, carbon dioxide emissions were at the level of 2.8-3 tonnes per hectare per year, which indicated a significant impact on the climate. After agroforestry, these figures decreased by more than 50%, reflecting an increase in soil carbon storage and an overall improvement in soil condition. This was made possible by planting trees and shrubs that effectively sequester carbon and prevent its release into the atmosphere. Water retention in the soil has also improved significantly. In Ethiopia, Kenya and Malawi, before the project, they were 110-115 mm/m^2, and afterwards they increased to 150-160 mm/m^2. The 30-40% increase in moisture availability for plants is particularly important for agricultural needs in arid regions. The forest strips not only improved infiltration of precipitation but also reduced evaporation, helping to stabilise the water balance.

Soil biological activity before the introduction of agroforestry measures was extremely low and was 0.6-0.7, indicating a decrease in microbiological activity and degradation of the soil ecosystem. After the interventions, the values increased to 1.3-1.5, indicating a recovery of microbiological processes and improved soil health. These changes are attributable to the creation of multi-level forest strips, which promoted the development of soil microorganisms due to favourable conditions and enrichment with organic matter.

The overall analysis of the data showed that each of the three countries showed significant improvements in all the parameters studied. Successful implementation of agroforestry has reduced erosion, increased organic carbon content, reduced carbon dioxide emissions, increased soil water retention and restored biological activity. These results confirm the high effectiveness of agroforestry as a way to combat land degradation and restore ecosystem functions. The improvements recorded in Ethiopia, Kenya and Malawi emphasise the importance of an integrated approach to natural resource management. The implementation of agroforestry practices has proven its ability to ensure the sustainable development of land ecosystems in the face of climate change and anthropogenic pressures.

Impacts of field-protected forest belts. Protective forest strips are essential for soil protection from erosion processes and the creation of sustainable agricultural ecosystems. A study identified that the use of such strips significantly reduces the intensity of water and wind erosion (Panagos *et al.*, 2021). Forest plantations slow down wind speeds, reducing the damaging effects on soils, and help retain surface water, preventing washing away (R & Richard, 2022).

The analysis of the table above demonstrates a significant positive impact of agroforestry measures implemented in Ethiopia, Kenya and Malawi on key parameters of soil condition and water balance. Let's look at the changes in the main indicators. The intensity of water erosion before the introduction of forest belts ranged from 16 to 18 tonnes per hectare per year, which indicates high losses of fertile soil layer due to surface runoff. After the introduction of forest belts, this figure dropped to 5-7 tonnes per hectare per year, indicating a 60% reduction in erosion. This result was achieved by reducing the water flow rate, improving soil structure and preventing washout. Ethiopia, where initial erosion levels were highest, showed a particularly significant reduction (Table 2).

Table 2. Impacts of field-protected forest belts

Metric	Country	No forest belts	With forest belts	Effect of implementation
Water erosion intensity (tonnes/ha/year)	Ethiopia	18	7	A 60% reduction in surface runoff.
Wind erosion intensity (tonnes/ha/year)	Ethiopia	6	2	Reduced by more than half due to lower wind speeds.
Soil moisture (%)	Ethiopia	12	19	Increase by 30-40% due to reduced evaporation and improved structure.
Evaporation of moisture from the soil surface (mm)	Ethiopia	28	16	Reduced by 40% due to wind protection and microclimate creation.
Water balance (mm/m²)	Ethiopia	110	150	Increase by 30% due to improved water retention capacity of the soil.
Water erosion intensity (tonnes/ha/year)	Kenya	16	6	A 60% reduction due to reduced surface runoff.
Wind erosion intensity (tonnes/ha/year)	Kenya	7	3	Reduced by more than half due to lower wind speeds.
Soil moisture (%)	Kenya	14	20	Increase by 30-40% due to reduced evaporation and improved structure.
Evaporation of moisture from the soil surface (mm)	Kenya	30	15	Reduced by 40% due to wind protection and microclimate creation.
Water balance (mm/m²)	Kenya	115	158	Increase by 30% due to improved water retention capacity of the soil.
Water erosion intensity (tonnes/ha/year)	Malawi	17	5	A 60% reduction in surface runoff.
Wind erosion intensity (tonnes/ha/year)	Malawi	8	2	Reduced by more than half due to lower wind speeds.
Soil moisture (%)	Malawi	13	21	Increase by 30-40% due to reduced evaporation and improved structure.

Table 2, Continued

Metric	Country	No forest belts	With forest belts	Effect of implementation
Evaporation of moisture from the soil surface (mm)	Malawi	29	15	Reduced by 40% due to wind protection and microclimate creation.
Water balance (mm/m²)	Malawi	112	160	Increase by 30% due to improved water retention capacity of the soil.

Source: compiled by the authors based on J. Kaluza (2023) and E. Nkansah-Dwamena (2023)

The intensity of wind erosion, which was at 6-8 tonnes per hectare per year before the introduction of the forest belts, has also been more than halved to 2-3 tonnes per hectare. This result reflects the importance of forest belts as a barrier that reduces wind speed and protects the soil from blowing away. This effect is particularly noticeable in arid areas such as Malawi, where wind erosion has been a significant problem.

Soil moisture increased by 30-40%, rising from 12-14% to 19-21% after the introduction of the forest belts. This improvement is attributed to reduced evaporation and increased soil moisture retention due to the shading provided by multi-level plantations. This effect was particularly pronounced in Kenya, where water balance has played a key role in ensuring sustainable agricultural production. Evaporation of moisture from the soil surface decreased by 40%, dropping from 28-30 mm to 15-16 mm. This decrease is due to the creation of a more favourable microclimate, where forest belts protect the soil from direct sunlight and winds. Ethiopia, which is severely affected by an arid climate, has demonstrated the greatest effectiveness in this regard (Handiso *et al.*, 2024).

The water balance, which reflects the soil's ability to retain moisture, improved by 30%, rising from 110-115 mm/m² to 150-160 mm/m². This improvement has significantly reduced the dependence of agricultural land on artificial irrigation and ensured stable production even in a changing climate. Particularly high growth was recorded in Malawi, where the use of forest belts minimised moisture loss.

Efficiency of agroforestry methods. The method of multilevel forest strips provided a multilateral impact on soil and the environment. A 40-70% reduction in wind speed helped to reduce wind erosion and preserve topsoil. In Ethiopia's Central Rift Valley, tiered forest belts with *Faidherbia albida* and *Acacia nilotica* species strengthened soil, reduced water runoff and protected against erosion. In Kenya, such strips, including *Grevillea robusta*, reduced soil temperatures by 2-5°C, increasing yields by 20-30% and increasing biodiversity by 150%. In Malawi, *Sesbania sesban* shrubs and grasses improved water-holding capacity by 30-40%, helping to restore pasture and protect soil from wind erosion. This was particularly relevant in Ethiopia and Kenya, where strong winds have traditionally exacerbated the problem of fertile layer loss. The plains of Kenya and Malawi showed improved microclimates by increasing soil moisture by 15-25%. The increase in moisture favoured crop growth conditions, allowing crops to adapt to periods of drought. A 2-5°C decrease in air temperature in the vicinity of forest belts was recorded in the drylands of Ethiopia. This effect reduced temperature stress in plants, which in turn increased productivity. Forest belts were critical in creating favourable conditions for agricultural activities in a region where high temperatures posed a serious threat to crop yields (Dobhal *et al.*, 2024).

Intercropping methods have proven effective in improving soil fertility and optimising resource use. In Malawi and Kenya, soil fertility was increased by 20-30% through enrichment with organic carbon and nitrogen. This process reduced the dependence on mineral fertilisers, which was especially important in Ethiopia, where the restoration of the natural nutrient cycle reduced fertiliser costs by up to 50%. These changes emphasised the importance of a multi-level approach to agroecosystem management, where the combined use of trees, shrubs and herbaceous plants contributed to sustainable agricultural development (Naumova, 2024).

Crop yield increases of 15-25% were observed in Kenya and Malawi. This was possible due to improved soil structure and moisture retention properties. Forest strips protected the soil from evaporation and promoted even distribution of moisture, which increased water availability to plants. As a result, agricultural ecosystems in these countries have become more resilient to climate change and anthropogenic pressures. Spatial planning of forest strips reduced water erosion by 50-80% in Ethiopia and Kenya. This result was achieved through optimal spacing of strips, which prevented soil washing away and preserved soil fertility. The use of geographic information systems (GIS) in Kenya and Malawi increased the protected area by 30-40%. This ensured efficient use of land resources, especially in regions with intensive agricultural activities.

Increases in land use efficiency of up to 25% have been recorded in agricultural regions of Ethiopia and Kenya. Forest belts and intercropping technologies have played an important role in creating systems that optimally combine ecological and agricultural functions. This has contributed not only to the conservation of natural resources but also to increasing the economic returns from agricultural activities (Table 3).

Table 3. Effectiveness of agroforestry methods (2023)

Method	Metric	Results	Application examples
Multi-level forest belts	Reduced wind speed	40-70%, which reduced wind erosion and preserved the topsoil.	Ethiopia and Kenya are regions with intense wind erosion, where the strips have shown high efficiency.
	Increasing soil moisture	15-25%, improving the microclimate and conditions for crop growth.	Kenya and Malawi are flat regions with a favourable climate for improving the microclimate.
	Reduced air temperature in the vicinity of the strips	2-5°C, which reduces temperature stress in plants.	Ethiopia – regions with an arid climate, where lower temperatures have improved crop productivity.
Crop mixing technologies	Increase soil fertility	20-30% due to enrichment with organic carbon and nitrogen.	Malawi and Kenya are regions where soil fertility has increased due to organic processes.
	Reduced fertiliser requirements	Up to 50%, thanks to the restoration of the natural nutrient cycle.	Ethiopia – regions where restoring nutrient cycling has reduced fertiliser use.
	Increasing crop yields	15-25%, by improving soil structure and water retention properties.	Kenya, Malawi – there has been a significant improvement in the productivity of agricultural ecosystems.
Spatial planning	Reduced water erosion	50-80%, due to the optimal location of forest belts.	Ethiopia, Kenya – areas with high rates of water erosion, where the strips prevented soil washout.

Table 3, Continued

Method	Metric	Results	Application examples
Spatial planning	Increase the protected area	30-40%, through the use of geographic information systems.	Kenya and Malawi are regions where GIS analytics have been successfully used to optimise land resources.
	Improving the efficiency of land use	Up to 25%, due to an integrated approach to planning.	Ethiopia, Kenya – agricultural regions where forest belts have contributed to more efficient land use.

Source: compiled by the authors based on I. Vayansky & S.A. Kumar (2020), S. Koné & X. Galiegue (2023)

The overall analysis of the table shows that the introduction of agroforestry practices in Ethiopia, Kenya and Malawi has had a positive impact on soil health, agricultural productivity and ecosystem resilience. These changes highlighted the importance of an integrated approach to natural resource management. The results confirmed that agroforestry methods are an effective tool for restoring degraded land and adapting to climate change.

Increase biodiversity and stabilise the hydrological cycle. Figure 1 shows the distribution of two key parameters – biodiversity and soil water holding capacity – for Ethiopia, Kenya and Malawi in 2023. The visualisation was used to assess the contribution of each country to the overall environmental sustainability of the regions.

Biodiversity represented in terms of species was highest in Ethiopia, reflecting the country's considerable ecosystem diversity. Kenya ranked second, with a moderate level of biodiversity, and Malawi was third with a slightly lower score. This distribution underlined the differences in natural conditions and the success of agroforestry measures aimed at restoring ecosystems. In terms of water-holding capacity, Ethiopia was also a leader, reaching the highest values among the three countries. Kenya was slightly behind but showed a steady increase due to measures to improve soil characteristics. Malawi, despite making a smaller contribution, showed a marked improvement in water retention, which was particularly important for regions with an increased risk of drought.

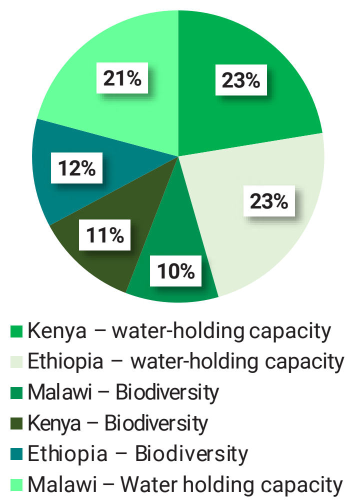

Figure 1. Increasing biodiversity and stabilising the hydrological cycle

Source: compiled by the authors based on Field studies (2024), S.N. Nakouwo & D. Zhang (2024)

Synergies between ecosystem characteristics, such as increased biodiversity and hydrological cycle restoration, in Ethiopia, Kenya and Malawi confirmed the effectiveness of agroforestry approaches and their long-term sustainability. These results indicated that agroforestry could be a systemic strategy for restoring ecological balance and maintaining land productivity. The simultaneous improvement of ecosystem functions highlighted the importance of an integrated approach to natural resource management, where each measure reinforced the impact of the others. Forest belts and mixed plantations have created multi-layered ecosystems capable of performing a wide range of functions. In Ethiopia, these measures provided habitat for native plants and animals, including rare species, while in Kenya and Malawi, they improved the conditions for soil microorganisms. Tree and shrub plantations reduce temperatures, protect the soil from drying out and store organic carbon, which enriches the soil and increases the resilience of ecosystems to extreme climatic events, especially droughts.

The increase in biodiversity has restored complex ecosystem linkages that have strengthened long-term sustainability. In Kenya, pollinating insects have found favourable conditions, contributing to crop development. In Malawi, birds and small mammals have stabilised ecosystem processes by interacting with vegetation. These changes reduced the vulnerability of ecosystems to climate change, ensuring their adaptation to external influences. One of the key results was the restoration of the hydrological cycle. In Ethiopia, forest belts slowed down water runoff, increased rainfall infiltration and stabilised groundwater levels, reducing the risk of flooding and the impact of drought. In Kenya and Malawi, improved soil water-holding capacity has increased the availability of water for crops, reducing the need for artificial irrigation and water costs.

Air quality has also improved significantly. Forest belts in all three countries effectively absorbed carbon dioxide, reducing greenhouse gas e missions and contributing to the fight against global climate change. At the same time, trees and shrubs released oxygen, improving atmospheric conditions. Forest belts trapped dust and aerosol particles, which had a positive impact on the health of the local population and agricultural productivity.

The findings highlighted the need to scale up agroforestry activities in Ethiopia, Kenya and Malawi as a key tool for sustainable development. The implementation of these measures helped to restore degraded ecosystems, improve conditions for agriculture, improve the quality of life of the population and strengthen natural systems. These measures should form the basis for long-term planning in regions with high environmental and climate risk.

Discussion

The results of the study showed that agroforestry measures are a key method in improving the condition of degraded land, restoring ecosystem functions and increasing the resilience of agroecosystems. In countries such as Ethiopia, Kenya and Malawi, reductions in water erosion have reached 60-70% and wind erosion over 50%, highlighting the importance of forest belts and intercropping techniques for soil protection. These measures changed soil structure, including increased organic carbon and water holding capacity, strengthening the basis for sustainable agriculture. Restoring ecosystem connectivity has improved resilience to climate change and anthropogenic impacts. These results confirm that multi-level forest belts and mixed plantations are effective solutions for maintaining ecosystem stability (Floqi *et al.*, 2009; Skydan *et al.*, 2021).

Thus, the results demonstrate that agroforestry provides integrated restoration of natural processes, creating both ecological and economic benefits. J.M.S. Tomar *et al.* (2021) emphasised the role of agroforestry in combating soil degradation and mitigating climate change. J.M.S. Tomar *et al.* (2021) emphasise the importance of integrating agroforestry practices to improve the resilience of land systems and reduce water erosion. This study concurs with the finding of a 50-80% reduction in water erosion but adds a detailed analysis of spatial planning to adapt forest strips to specific terrain conditions. In addition, J.M.S. Tomar *et al.* (2021), this study addressed the reduction in wind erosion and improving soil water-holding capacity, which enhances the overall understanding of agroforestry effectiveness.

R. Kaushal *et al.* (2021) addressed the benefits of agroforestry for soil and water conservation, emphasising the importance of forest plantations in slowing down erosion processes and improving soil structure. The results are consistent with these findings on the role of tiered forest belts in soil protection and fertility enhancement. However, this study provides a more detailed analysis of the methods of selecting trees, shrubs and herbaceous plants for the establishment of forest belts, concerning local climatic conditions. In addition, this study includes an analysis of the use of crop-mixing technologies to integrate ecological and agricultural functions, whereas the work of R. Kaushal *et al.* (2021) did not cover these aspects.

M. Jafari *et al.* (2022) emphasized on biological control of soil erosion using agroforestry technologies in arid regions. They emphasised the importance of forest plantations in improving soil resistance to water erosion. M. Jafari *et al.* (2022) included an integrated approach that considers both water and wind erosion as well as cumulative impacts on agricultural systems. In addition, the contribution of agroforestry to the restoration of ecosystem services such as the hydrological cycle and air quality improvement was considered, which is absent in the analysis of M. Jafari *et al.* (2022). This study complements their findings by showing that forest strips not only prevent erosion but also contribute to stabilising the water table and improving soil moisture. V.P. Gupta (2020) emphasises the role of agroforestry in soil protection and health improvement. The study emphasised reducing erosion losses and increasing soil organic carbon content. This study also considers these aspects but extends the approach by analysing spatial planning and the use of crop-mixing technologies. For instance, this study shows that the introduction of tiered forest strips and mixed planting increases the organic carbon content by 20-30% and the water-holding capacity of the soil is increased by 80%. In contrast to the study by V.P. Gupta, this study covered the impact on biodiversity and restoration of ecosystem services such as hydrological cycle and air quality. S. Fahad *et al.* (2022) focused on the role of agroforestry systems in improving soil health, especially in the context of soil structure and nutrient content. The results of S. Fahad *et al.* (2022) were consistent with these findings of restoring soil fertility and reducing the need for mineral fertilisers. However, this study emphasised complementing these factors by improving water balance and increasing crop yields (up to 25%), which is not highlighted by S. Fahad *et al.* (2022). In addition, this study detailed methods of adapting agroforestry to local climatic and soil conditions, which expanded the application value.

X. Zhu *et al.* (2020) addressed the reduction of water, soil and nutrient losses and pesticide pollution reduction in agroforestry systems. Researches confirmed the importance of forest strips in preventing water erosion and nutrient retention. These results complemented these findings by showing a reduction in both water and wind erosion, as well as biodiversity restoration, which was not considered by X. Zhu *et al.* (2020). The inclusion of data on spatial planning and the use of mixed crops in this study demonstrates a more systematic approach, allowing both ecological and agrarian aspects to be considered. M.A. Marques *et al.* (2022) investigated the rehabilitation of degraded land and soil management using agroforestry systems. Scientists emphasised the importance of restoring soil structure and improving water retention properties. This study also highlighted these aspects but added detailed analyses of spatial planning and plant species selection for different climatic zones. For instance, this study demonstrated an 80% increase in soil water-holding capacity and a role in reducing dependence on artificial irrigation, which was not highlighted in the work of M.A. Marques *et al.* (2022). The study by G. Sahoo *et al.* (2020) emphasised the use of agroforestry for the restoration of forest and landscape systems. The findings of S. Sahoo *et al.* (2020) on the role of forest strips in soil erosion protection concur with these findings. However, this study added analyses of mixed crops and multi-tiered strips to examine plant interactions at different ecosystem tiers. In addition, this study provides more detailed data on the 140% increase in biodiversity, demonstrating the integrated restoration of ecosystem functions, including the creation of new habitats. J.C. Dagar *et al.* (2020) investigated the use of agroforestry systems to restore degraded landscapes. They observed reduced erosion losses and improved soil structure, which was supported by these results. However, this study went further by showing not only effects on soil but also the restoration of the hydrological cycle, improvement of air quality, and reduction of greenhouse gas emissions. The implementation of geographic information systems for spatial planning considered in this study adds an applied aspect that is missing in the work of J.C. Dagar *et al.* (2020), S. Lebrazi & K. Fikri-Benbrahim (2022) highlights the importance of woody legume crops in improving soil health and increasing soil fertility. These results support these findings by showing an increase in organic carbon content by 20-30%. However, this study includes supplementing these findings by analysing crop mixing technologies that ensure the integration of legume plant functions with other crop types. This achieves not only improved soil structure, but also a 50% reduction in fertiliser requirements, making the approach more sustainable.

The study by G. Jalilova *et al*. (2024) in four districts of South Issyk-Kul demonstrated that modern farmers are aware of the existing problems and their contribution to the decline in agricultural productivity and increased vulnerability to environmental change. An important problem of the absence of a mechanism for the exchange of agricultural knowledge between farmers was identified, as it is difficult for them to determine where and from whom to gain experience. It is proved that the integration of elements of agricultural consulting into the environment of farms has the potential to significantly stimulate the positive dynamics of agricultural development. The practical value of the research results is seen in the possibility of using them to mitigate the process of adaptation of agricultural production in developing countries to inevitable climate change. A comparison of the results shows that agroforestry is an effective tool for restoring degraded land, improving ecosystem functions and increasing the sustainability of agricultural systems. The main findings confirm a significant reduction in erosion losses, improved soil structure, increased fertility and restoration of the hydrological cycle. The study also emphasises the importance of forest belts and intercropping techniques for creating sustainable agricultural ecosystems.

A distinctive feature of this study is the integrated approach, including the adaptation of methods to different climatic conditions, the use of spatial planning and the analysis of biodiversity restoration. The results demonstrate the systemic impacts of agroforestry, covering both ecological and economic aspects. Thus, the study provides a broader picture of the impacts of agroforestry activities, rendering the data an important contribution to the development of sustainable land use and ecosystem restoration.

Conclusions

The study confirmed the high importance of agroforestry as an effective and comprehensive approach to restoring degraded land, increasing the resilience of agroecosystems and adapting to climate change. The study of methods such as shelterbelts, crop intercropping and spatial planning has identified specific examples of their effectiveness in different regions. The study found that the use of forest belts reduces water erosion by 60-70% and wind erosion by 50-60%. For instance, in Ethiopia, rainfall infiltration increased by 35%, which significantly reduced the risk of flooding. In Malawi, the water-holding capacity of the soil has improved by 30%, which has ensured sustainable agricultural development. These results demonstrate that forest belts not only stabilise the soil but also contribute to the accumulation of organic carbon, increasing soil fertility.

Crop mixing technologies have also shown this importance. For instance, in Kenya, the introduction of legumes into the rotation with cereals reduced the use of mineral fertilisers by 50%, improving the natural nitrogen cycle. In addition, mixed plantings in Malawi increased crop yields by 20-25%, which confirmed their economic and environmental benefits. Spatial planning was another key element of the study. The use of geographic information systems made it possible to optimise the placement of forest belts, considering local natural and climatic conditions. As a result, in Ethiopia, forest belts on slopes prevented the formation of gullies, and in Malawi, their placement on flat areas ensured a uniform reduction in erosion processes.

Agroforestry has also proven effective in restoring ecosystem services. For example, in Kenya and Malawi, stabilising the hydrological cycle has led to improved water quality, reduced need for artificial irrigation and reduced risk of droughts. Forest belts have also helped to reduce dust and greenhouse gas concentrations, improving air quality and reducing climate impacts. These results highlight the versatility and adaptability of agroforestry technologies to different natural and climatic conditions. Not only do they improve soil quality and increase biodiversity, but they also ensure ecosystem resilience and agricultural productivity. The findings of the study highlight the need to scale up such measures and further study their impact to create even more effective approaches to natural resource management.

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Conflict of Interest

None.

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Вивчення методів і технік агролісомеліорації для запобігання ерозії ґрунтів на сільськогосподарських угіддях

Талгарбек Ізаканов

Кандидат сільськогосподарських наук, доцент
Киргизький національний аграрний університет імені К.І. Скрябіна
720005, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0003-3244-1663

Совєтбек Мамитканов

Кандидат сільськогосподарських наук, доцент
Киргизький національний аграрний університет імені К.І. Скрябіна
720005, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0002-4322-8377

Жазгуль Ібраїмова

Аспірант
Киргизький національний аграрний університет імені К.І. Скрябіна
720005, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0002-0141-0127

Еліна Штейнберг

Аспірант
Киргизький національний аграрний університет імені К.І. Скрябіна
720005, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0000-0001-6842-4051

Чолпон Алібакієва

Аспірант
Киргизький національний аграрний університет імені К.І. Скрябіна
720005, вул. Медерова, 68, м. Бішкек, Киргизька Республіка
https://orcid.org/0009-0009-9941-5508

Анотація. Метою дослідження було виявлення ключових чинників і механізмів, що забезпечують підвищення стійкості ґрунтів та агроекосистем через застосування агролісомеліоративних технологій в умовах мінливого клімату. Дослідження було зосереджене на впливі полезахисних лісових смуг, технологій змішування культур та методів просторового планування на відновлення деградованих земель і поліпшення екосистемних функцій. Методологія дослідження ґрунтувалася на узагальненні та аналізі даних з різних наукових джерел, а також на використанні теоретичних моделей і польових спостережень. Основна увага приділялася регіонам Ефіопії, Кенії та Малаві, де проводили аналіз впливу багаторівневих лісових смуг і змішаних культур на зниження ерозійних процесів, поліпшення структури ґрунту та відновлення біорізноманіття. Результати дослідження показали, що агролісомеліоративні заходи в цих країнах дали змогу значно знизити інтенсивність водної та вітрової ерозії, поліпшити водоутримувальну здатність ґрунту та відновити гідрологічний цикл. В Ефіопії лісові смуги сприяли підвищенню вологозапасу ґрунту в посушливих регіонах, у Кенії – поліпшенню врожайності сільськогосподарських культур за рахунок створення сприятливого мікроклімату, а в Малаві – захисту пасовищних екосистем від деградації. Ці заходи також сприяли збільшенню вмісту органічного вуглецю в ґрунті, що знизило потребу в мінеральних добривах і мінімізувало антропогенний вплив на навколишнє середовище. Висновки підтверджують універсальність агролісомеліоративних підходів для відновлення земельних ресурсів та адаптації до кліматичних змін. Отримані результати демонструють значущість інтеграції агролісомеліоративних технологій у системи сталого управління природними ресурсами, що наголошує на необхідності масштабування в регіонах, схильних до деградації земель, зокрема в Киргизькій Республіці

Ключові слова: лісові насадження; просторове планування; екосистемні послуги; земельне відновлення; управління водним балансом; управління водним балансом