Полученные результаты имеют важное практическое значение для разработки систем раннего предупреждения и управления природными рисками в горных регионах. В условиях роста среднегодовых температур и ускоренного таяния ледников необходимость детального мониторинга ледниковых озер становится особенно актуальной, что требует дальнейшего совершенствования методов дистанционного зондирования и их интеграции с наземными наблюдениями.

Ключевые слова: Моренные озера, ДЗЗ, ГИС, изменение климата, прорывоопасность, селевые потоки, Центральная Азия, ледники

IRSTI 68.47.94; 68.47.15; 68.47.33 **DOI** https://doi.org/10.37884/2-2025/48

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FOREST ECOSYSTEMS OF EAST KAZAKHSTAN IN THE SYSTEM OF WATER BALANCE REGULATION AND SOIL EROSION PROTECTION

Abstract

The article examines the impact of forest ecosystems in Eastern Kazakhstan on the regulation of water balance and protection of soils from degradation. Experimental studies have been conducted to assess the water retention capacity of soils, the level of erosion and the dynamics of humidity in various forest formations. The results show that forests play an important role in stabilizing the hydrological regime and preventing erosion processes. Remote sensing data and GIS technologies have been applied to analyze vegetation cover density, soil moisture indices, and NDVI values, which provides a comprehensive assessment of ecosystem health. The study also examines the role of tree and shrub composition in erosion resistance, highlighting the importance of mixed forest formations in increasing soil stability. The results highlight the need for sustainable forest management practices and afforestation strategies to mitigate land degradation and improve regional water conservation efforts. Analysis of precipitation infiltration and evapotranspiration rates shows that forests contribute to maintaining stable groundwater levels, reducing the risk of droughts and floods in adjacent agricultural and urban areas. The study concludes with recommendations for adaptive management strategies for forest conservation, including afforestation using native species, controlled grazing methods, and the implementation of solutions based on natural factors to enhance landscape resilience. These findings serve as the basis for the development of a comprehensive policy aimed at preserving the ecological functions of forests in Eastern Kazakhstan and ensuring long-term environmental sustainability.

Keywords: *forests, water balance, soil erosion, soil degradation, East Kazakhstan.*

Introduction

Forest ecosystems play a key role in ensuring the sustainability of natural landscapes, shaping water balance, and preventing soil degradation [1]. In Eastern Kazakhstan, where the continental climate prevails with sharp temperature fluctuations and uneven precipitation distribution, forest conservation is a critically important aspect of the ecological stability of the region [2]. In recent decades, active land development, deforestation and climate change have led to an increased risk of soil erosion and a decrease in their water retention capacity [3].

The water balance of the territory is determined by a number of factors, among which vegetation plays an important role. Forests are able to retain significant amounts of moisture, reducing evaporation and increasing precipitation infiltration into the soil. In addition, the root system of the trees helps to consolidate the soil and prevents water and wind erosion. In the mountainous and foothill regions of Eastern Kazakhstan, forests perform even more important functions, preventing catastrophic landslides and mudflows that can occur due to intense precipitation [4, 5].

The main problem of the region is related to the degradation of soils due to their over-compaction, reduction of organic matter and erosion processes. Intensive pasture use and expansion of agricultural land often lead to deterioration of the soil cover, which in the long term can affect land productivity. In this context, forests are not only a source of biological diversity, but also an important element of natural regulation of hydrological processes [6].

The purpose of this study is to analyze the water-retaining characteristics of soils in the forest ecosystems of Eastern Kazakhstan, assess the level of erosion and determine the contribution of forests to the regulation of water balance. To achieve this goal, field experiments were conducted, including measurements of soil moisture capacity, infiltration rate, and erosion resistance in various types of woodlands. Open steppe areas subject to natural degradation processes were used as a control group [7-9].

The scientific significance of the study lies in the identification of specific mechanisms through which forests contribute to the conservation of water resources and the prevention of loss of fertile soil. The practical significance of the work is related to the development of recommendations on reforestation and effective environmental management in arid and continental climates. The article also examines the prospects for the introduction of forest plantations into the agro-landscapes of the region in order to increase their resistance to changing climatic conditions [10].

Thus, the study is aimed at a comprehensive study of the impact of forests on the hydrological regime of the region and the protection of soils from degradation. The results can be useful for ecologists, specialists in the field of soil science and land use, as well as for government agencies involved in environmental protection and sustainable agricultural development [11].

Materials and methods

The study was conducted on the territory of East Kazakhstan in 2023-2024. Three experimental sites have been selected. Mountain coniferous forests (spruce, pine) are characterized by dense stands and a well–developed root system, which contributes to the high water retention capacity of soils. Deciduous forests (birch, aspen) have a moderate density of tree cover, but a higher seasonal dynamics of moisture accumulation. Steppe areas (control group) are represented by grassy vegetation, are subject to high evaporation and active erosion processes [12-14].

Hydrological analysis. The hydrological analysis included the study of the soil water regime and the dynamics of moisture availability, which was of key importance for assessing the processes of erosion, land degradation and ecosystem sustainability. Determination of soil moisture capacity by gravimetric analysis. To assess the moisture capacity of the soils, samples were taken at different depths (0-10 cm, 10-30 cm, 30-50 cm) [15].

Samples were taken using standard soil drills or cylinders. Fresh samples were weighed and dried in a drying cabinet at a temperature of 105 °C to a constant weight. The percentage of moisture in the soil was re-weighed and calculated. Measurement of water infiltration using double cylinder infiltometers. The method allowed us to estimate the rate of water absorption by the soil and the permeability of soil horizons [16].

Two concentric metal cylinders were inserted into the soil. The inner and outer cylinders were filled with water and the rate of water seepage into the soil was recorded. The infiltration coefficient was determined based on changes in the water level. Evaporation analysis by installing evaporator cups. The method made it possible to measure the intensity of evaporation of water from the surface of the soil and vegetation. Evaporation cups were installed in control areas with different types of vegetation [17]. The water level in the cups was regularly measured, which made it possible to determine moisture loss. The data obtained was used to assess the water balance of the territory.

Soil research. The complex of soil studies made it possible to study in detail the physico-chemical properties of the soil, which are important for understanding the processes of degradation, erosion and productivity of land [18].

Soil structure analysis by sieve analysis. The granulometric composition of the soil affected the water retention capacity and resistance to erosion. The samples were dried and sieved through a set of sieves of various diameters (for example, 2 mm, 0.5 mm, 0.25 mm, etc.). The percentage of sand, silt, and clay was calculated by the mass of the fractions. The data obtained was used to classify the soil type [19].

Determination of humus content by Turenne method. Turenne's method was based on the oxidation of organic matter in the soil, which made it possible to determine the level of fertility. The soil samples were treated with a solution of potassium bichromate in sulfuric acid [20]. After the chemical reaction, the intensity of staining of the solution was evaluated. The percentage of humus in the soil was calculated.

Mechanical soil analysis. The soil samples were mixed with a dispersant to destroy the aggregates. The sedimentation method was used, in which particles of different sizes settled in water at different speeds. The proportions of sand, silt and clay were determined, which made it possible to assess the water-holding capacity of the soil. Determination of soil resistance to water erosion. Under laboratory conditions, the samples were exposed to a stream of water of varying intensity. The process of soil erosion on the simulated slopes was studied in the field. The parameters of soil resistance to erosion and erosion were determined [21].

Erosion monitoring. Erosion monitoring methods have made it possible to quantify the processes of soil destruction. Setting reference points. The reference points were fixed on the ground, which made it possible to measure soil flushing throughout the year. They were installed in areas with varying degrees of forest cover and slope. Periodic measurements of the soil levels around the reference points were carried out. The intensity of soil flushing was estimated depending on weather conditions. Using precipitation meters. Sedimentation meters were used to measure the amount of sediment formed as a result of erosion.

Special tanks were installed in the relief depressions. After the rains and snowmelt, accumulated soil particles were measured. The dynamics of erosion processes depending on the season was analyzed. Geodetic measurements of relief changes. Digital profilers were used to create topographic profiles of the area. Changes in the depth of gullies and gullies were monitored. Forecasts of soil degradation were modeled.

Satellite analysis and remote sensing. Modern remote sensing methods have made it possible to conduct large-scale studies of soils and vegetation with high accuracy. Using NDVI data and humidity indices. NDVI (normalized difference vegetation index) was calculated based on satellite images, which reflected the state of vegetation. Humidity indices (for example, NDMI – normalized humidity index) were used to estimate the moisture content in the soil. The data was analyzed over time to identify changes in vegetation cover. Comparative analysis of long-term satellite data from Landsat and Sentinel-2. We analyzed images from different years to identify trends in soil degradation. The density of vegetation cover and the degree of soil moisture were assessed. We have identified areas subject to increased erosion. Analysis of topographic and climatic data. We have created digital terrain models based on satellite data. The water balance of the territory was modeled taking into account climatic factors. Degradation processes were predicted based on the analysis of trends in soil moisture [22, 23].

The use of complex research methods allowed us to obtain a detailed picture of hydrological processes, dynamics of soil characteristics and erosion processes. The use of satellite analysis and geodetic measurements expanded the possibilities of monitoring and forecasting degradation processes, which was important for the conservation of land resources.

Results and discussion

The results of the soil moisture capacity analysis showed that forest soils retain 25-40% more moisture than steppe areas. This is due to the high content of organic matter and the developed root system of trees, which promotes the penetration of water into the soil.

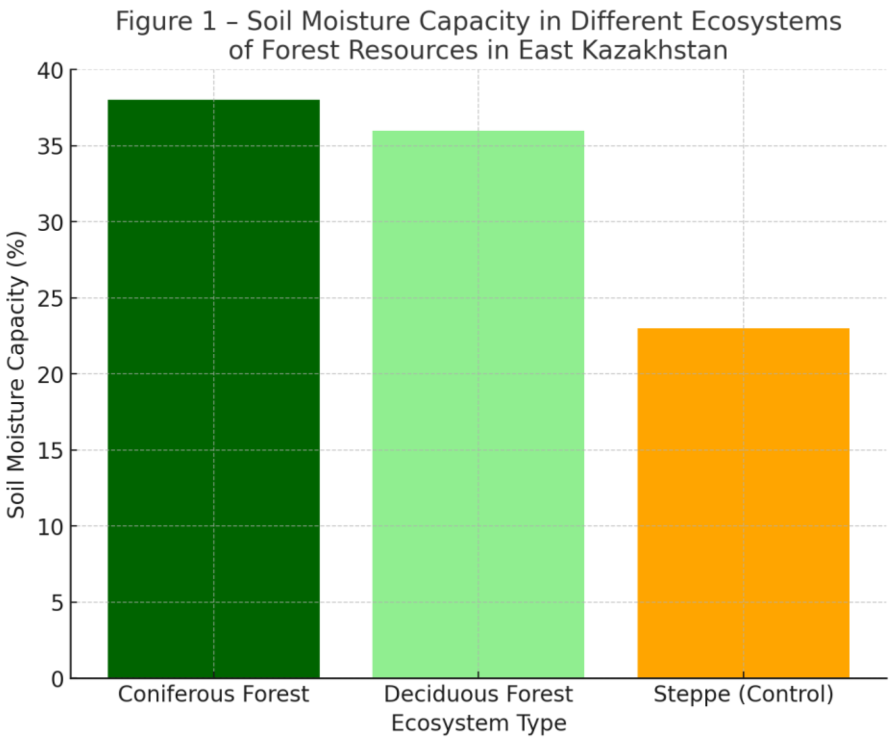

Figure 1 –Soil moisture capacity in different ecosystems of forest resources in EastKazakhstan

As can be seen from Figure 1, when comparing different ecosystems - coniferous forest, deciduous forest and steppe, the steppe zone was taken as the control. Main observations. Coniferous forest ha 38-39%; Deciduous forest follows 36-37%; Steppe (control) exhibits are 23-24%. Forest ecosystems (both coniferous and deciduous) retain significantly more soil moisture than the steppe ecosystem.

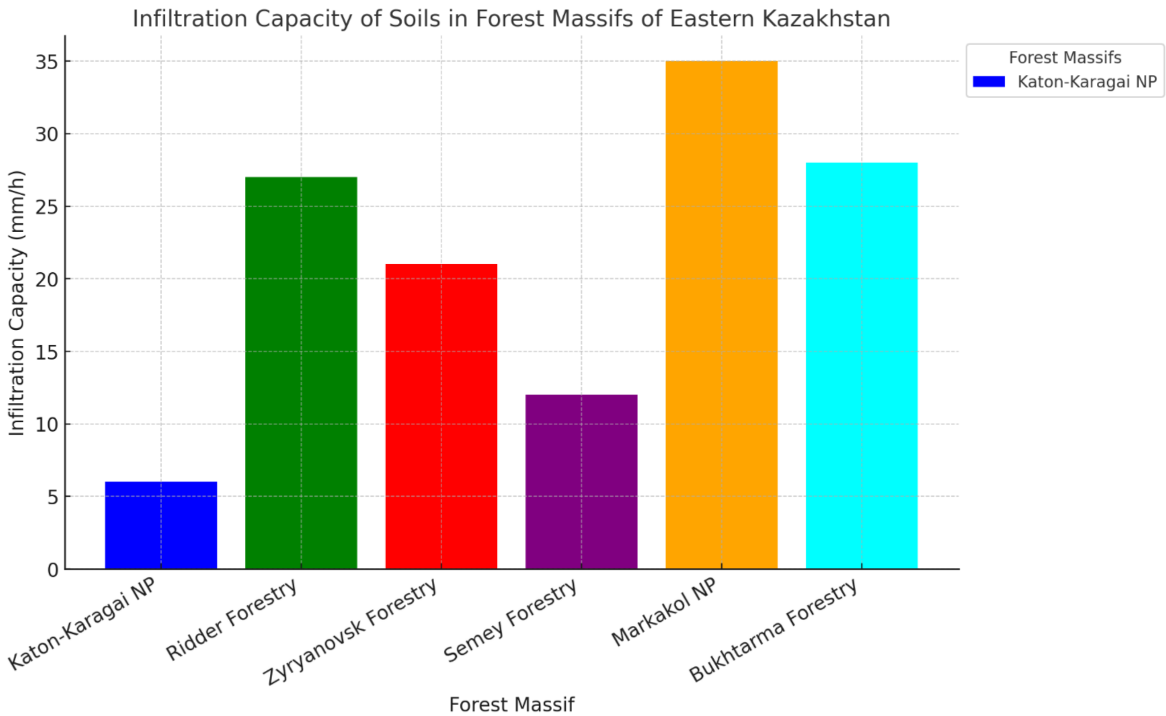

Figure 2 – Infiltration capacity of soils in forest areas of Eastern Kazakhstan

Markakol NP demonstrates 35 mm/hr, which indicates. Bukhtarma forestry follows 28 mm/h. Ridderaal forestry 26 mm/h. Zyryanovsky forestry 21 mm/h. Semey forestry has a significant 11 mm/h. Katon-Karagai NP has the lowest infiltration capacity, 5 mm/h.

Changes in the infiltration capacity of soil composition, vegetation cover, organic matter content and land management methods. Markakolsky NP and Bukhtarma forestry are characterized by a low rate of infiltration. In the Katon-Karagai NP, it may indicate a higher surface runoff and lower water retention. Forests with a higher infiltration capacity contribute to groundwater replenishment.

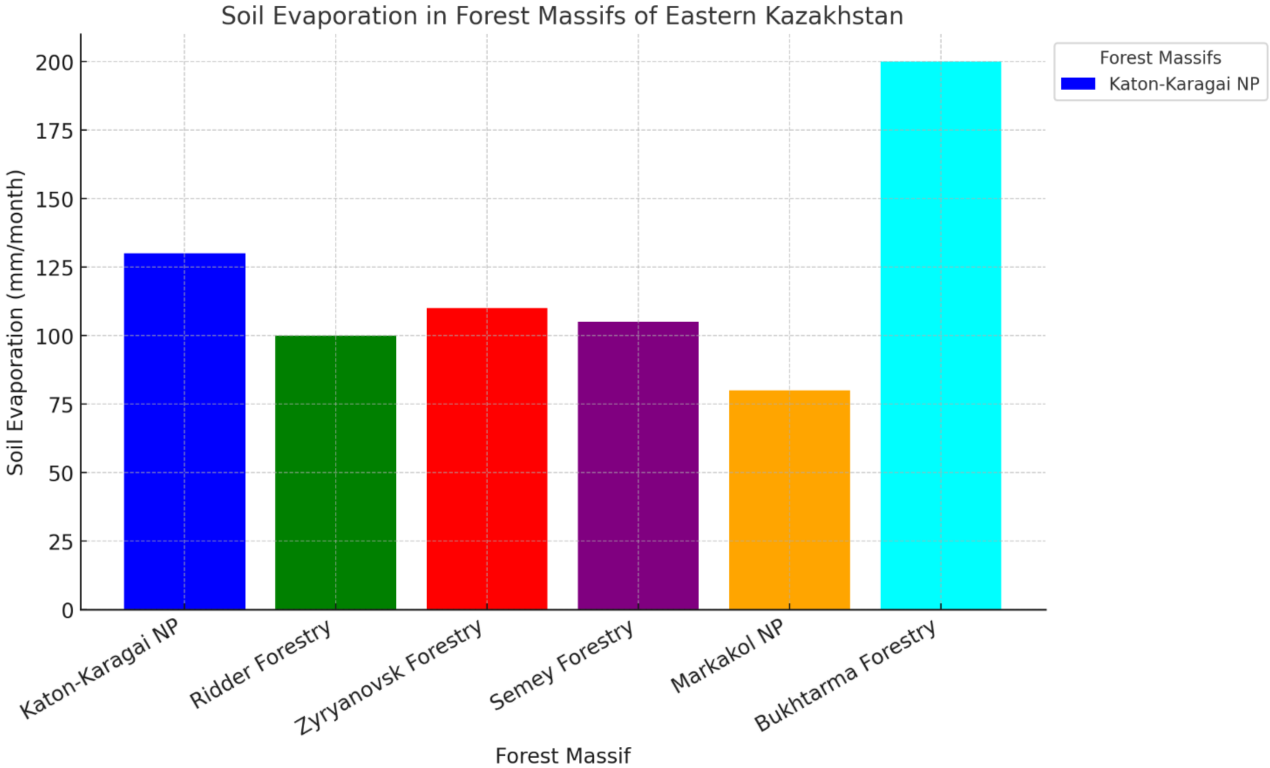

Figure 3 - Soil evaporation in the forest area of East Kazakhstan

Bukhtarma forestry demonstrates the highest rate of soil evaporation, 200 mm/month. Katon-Karagai NP is also 130mm/month. The Zyryanovsky forestry and the Semey forestry have moderate 110mm/month. The forestry of the Reader has 100 mm/month. Markakolsky NP is the lowest evaporation rate, at 80 mm/month.

Higher soil evaporation in Bukhtarma forestry and Katon-Karagai NP indicates higher temperatures, lower humidity or a decrease in canopy cover. Lower evaporation rates in NP Markakol for better moisture retention. Differences in the rate of soil evaporation include microclimate, soil properties, and vegetation density. These data can be useful for understanding water balance, soil moisture conservation strategies, and sustainability of forest ecosystems.

Figure 4 shows various soil parameters in different woodlands, including granulometric composition, humus content, sand content, silt content, clay content, and erosion resistance. The sand content (orange columns) is the highest in all forests, especially in the Zyryanovsky forestry (~72%), which indicates a loose soil structure prone to water drainage. The granulometric composition (blue columns) is relatively high, especially in Riddersky forestry, Katon-Karagaysky NP and Zyryanovsky forestry (~50-60%), which indicates a well-developed soil structure. The clay content (purple columns) varies, but remains moderate (~25-30%) in most areas, with the exception of the Semeysky forestry and Bukhtarma forestry, where it is slightly lower. The sludge content (red columns) is usually low, about 10-15%, indicating a limited accumulation of fine particles.

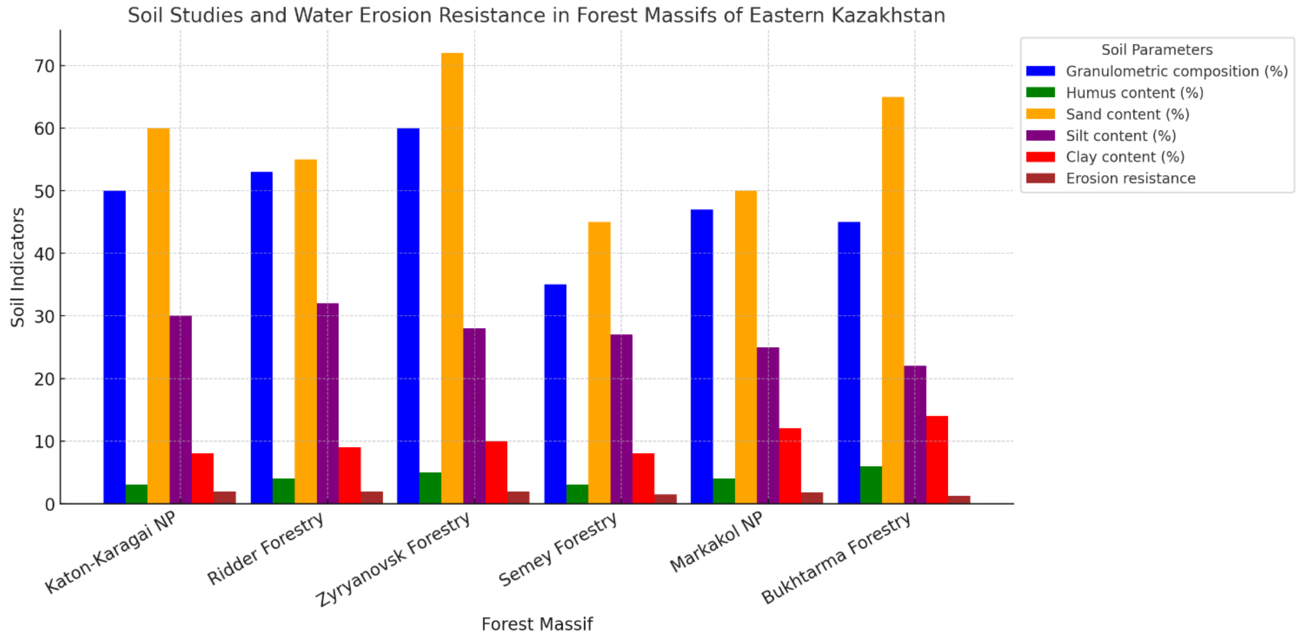

Figure 4 - Soil resistance of various forestry zones to water erosion in the conditions of Eastern Kazakhstan

The humus content (green columns) is consistently low in all massifs, which indicates a low content of organic substances and a possible susceptibility to erosion. Erosion resistance (brown columns) is minimal, and all woodlands exhibit low resistance, which makes them potentially vulnerable to soil degradation. The high sand content in areas such as the Zyryanovskoye forestry suggests rapid water filtration, but poor moisture retention, which makes these soils susceptible to erosion without proper vegetation cover. The moderate clay content contributes to some water retention, but it can still allow surface runoff, which increases the risk of erosion. The low humus content in all massifs indicates a poverty of organic substances, which can affect soil fertility and stability of its structure. Erosion resistance is generally low, indicating that most woodlands require sustainable soil conservation methods to prevent degradation.

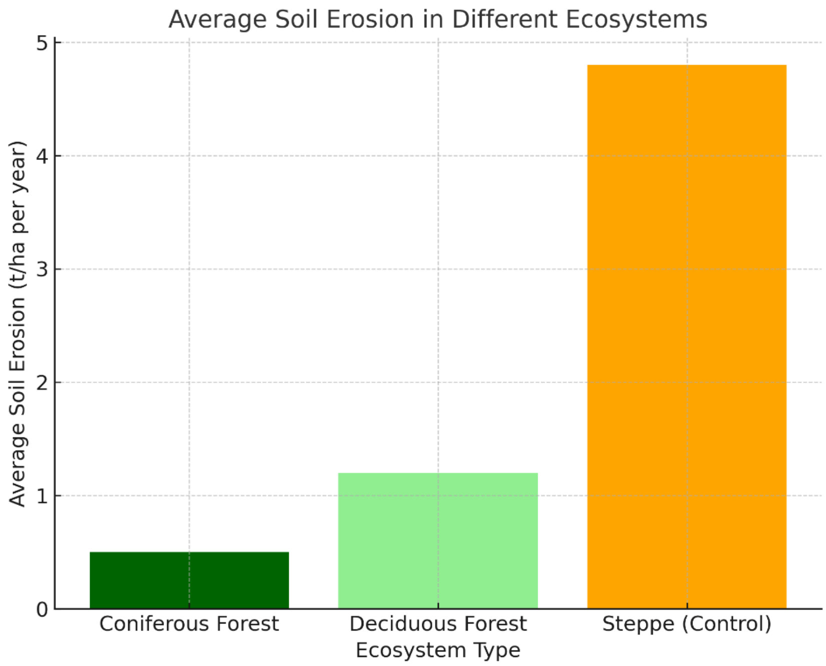

Figure 5 – Indicators of soil erosion in forest ecosystems of East Kazakhstan

The soils of the forests of Eastern Kazakhstan have moderate structural stability, but are at risk of erosion due to their high sand content, low humus content and low resistance to erosion. Strategies such as reforestation, mulching, and controlled land use can help improve soil stability and water retention.

Control measurements of soil washout showed that in the steppe zone the loss of the fertile layer is 3-4 times higher than in the forest zones. In coniferous forests, erosion is minimal due to dense vegetation cover and a layer of litter, which reduces the impact of precipitation.

The steppe (control) has the highest level of land washout - 5 t/ha per year. Deciduous forest shows a moderate level of soil erosion – approximately 1.2 t/ha per year. Coniferous forest has the least erosion – about 0.5 t/ha per year. Forest ecosystems (coniferous and deciduous forests) significantly reduce land washout compared to open steppe areas. This is due to the higher content of organic substances. The steppe (control) shows the highest level of erosion, which is associated with the open terrain and the absence of dense vegetation, with a low content of humus and loose soil structure.

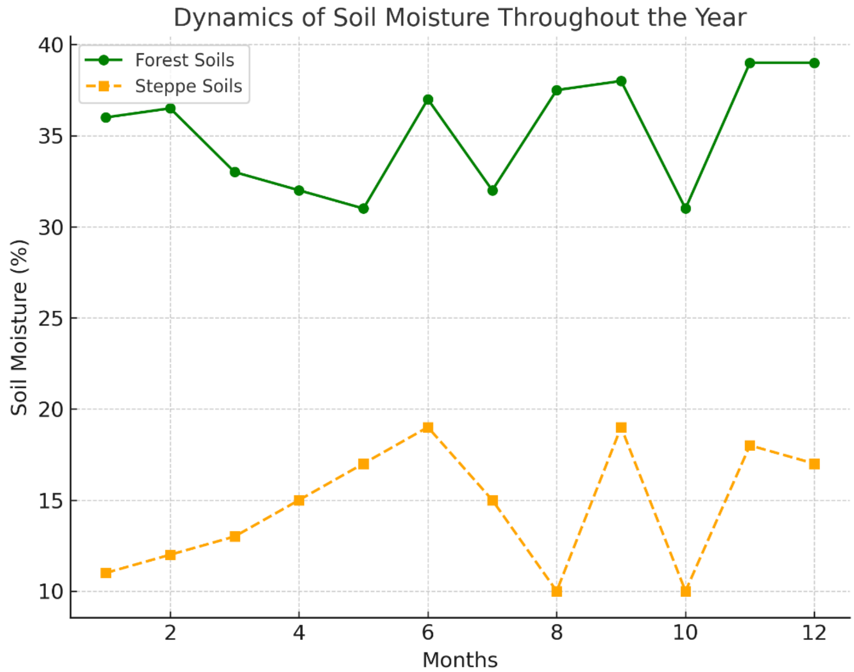

Figure 6 – Dynamics of soil moisture in different ecosystems during the year (average over 3 years)

The chart illustrates the monthly dynamics of soil moisture in forest and steppe soils. Forest soils consistently maintain higher moisture levels (around 31–39%) throughout the year, with relatively stable fluctuations. In contrast, steppe soils show greater variability, ranging from 10% to 19%, with noticeable drops in August and October. Overall, forest soils exhibit better moisture retention compared to steppe soils.

Spectral Vegetation Analysis refers to the use of remote sensing data to assess and monitor vegetation characteristics based on how plants reflect and absorb electromagnetic radiation across different wavelengths.

Table 1 -The ratio of woody, shrubby and herbaceous species using spectral analysis

№	Forest Massif	Tree Cover (%)	Shrub Cover (%)	Grass Cover (%)
1	Katon-Karagai NP	65	20	15
2	Ridder Forestry	70	18	12
3	Zyryanovsk Forestry	68	22	10
4	Semey Forestry	62	25	13
5	Markakol NP	60	27	13
6	Bukhtarma Forestry	66	23	11

This table shows the percentage of tree, shrub, and herbaceous species coverage in various forests of Eastern Kazakhstan based on spectral analysis. The highest tree cover is observed in Riddersky forestry (70%), followed by Zyryanovsky forestry (68%) and Katon-Karagaysky NP (65%). The lowest tree cover is observed in Markakolsky NP (60%), which indicates a relatively higher proportion of shrubs and herbaceous vegetation. In general, all woodlands have more than 60% tree cover, which confirms their characteristics of dense forest.

4. Satellite monitoring of soil moisture

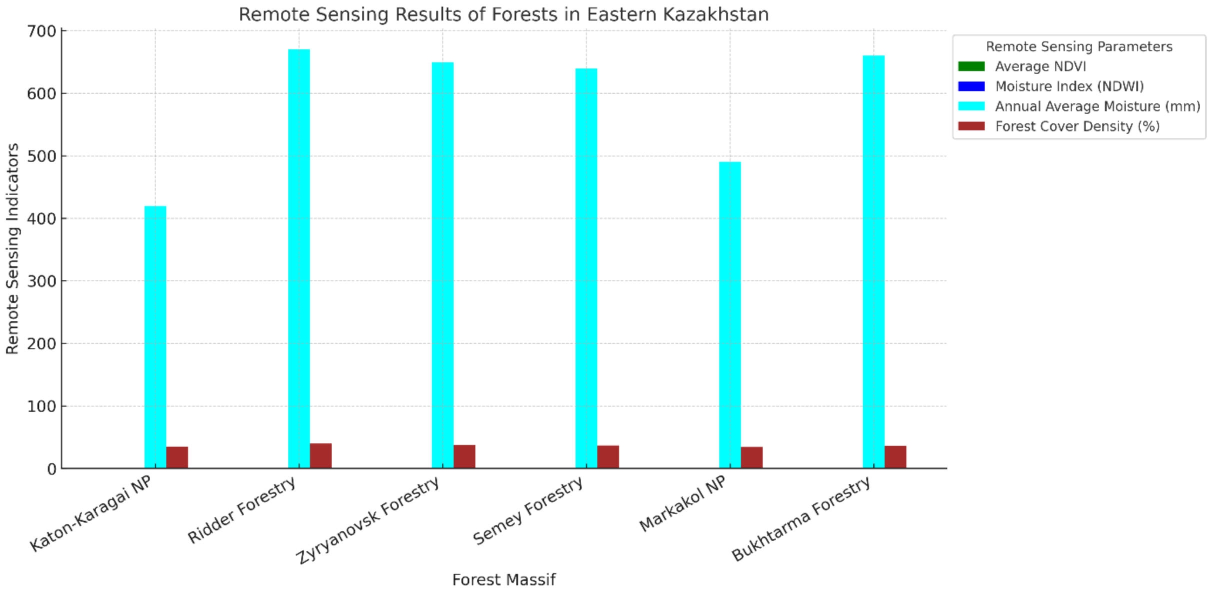

Figure 7 – Results of remote sensing of forest resources in East Kazakhstan

Figure 7 shows remote sensing indicators for various forests in Eastern Kazakhstan, including the normalized vegetation difference index (NDVI), humidity index (NDWI), average annual humidity (mm), and forest cover density (%). The highest values (~650-700 mm) are observed in Ridder Forestry, Zyryanovsky Forestry, and Bukhtarma forestry., which indicates a high amount of precipitation or moisture retention in the soil. Katon-Karagai NP and Markakol NPF show lower humidity values (~400-500 mm), which indicates drier conditions or lower retention capacity.

The highest NDVI index (~0.75) was recorded in Ridder Forestry, which indicates dense and healthy vegetation. The Zyryanovsky forestry and Bukhtarma forestry also show a relatively high NDVI index (~0.71–0.73), which indicates good forest cover and healthy plant growth.

The Katon-Karagai National Park (~0.69) and the Semey Forestry (~0.70) have a moderate vegetation density, indicating a combination of forest and open areas.

NP Markakol (~0.66) has the lowest NDVI index, which indicates a lower vegetation density or potential degradation of forest cover.

Higher NDVI values (0.71–0.75) in Riddersky, Zyryanovsky and Bukhtarma forestry indicate a better forest condition, greater biomass and denser forest cover. Lower NDVI values (~0.66–0.69) in Markakol NP and Katon-Karagai NP may indicate sparser vegetation, potential deforestation, or more severe climatic conditions.

Woodlands at higher latitudes (in the north), such as Riddersky forestry and Zyryanovsky forestry, are characterized by better vegetation conditions. The southern regions (Markakol National Park, Katon-Karagai National Park, Bukhtarma Forestry) show lower NDVI values, possibly due to fluctuations in altitude, differences in precipitation, or the influence of land use.

Remote sensing data confirmed significant differences in soil moisture dynamics between forest and steppe areas. Forests contribute to the preservation of moisture throughout the growing season, while steppe areas experience a shortage of moisture during dry periods.

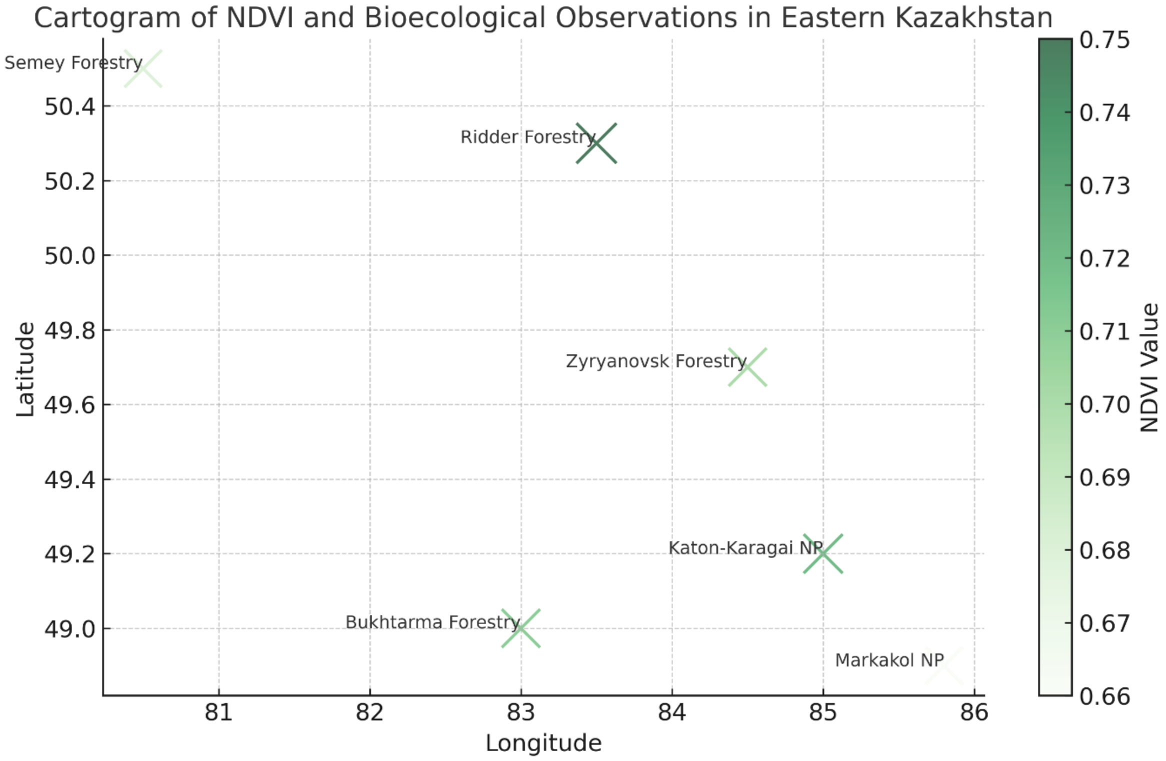

Figure 8 – Cartogram for the integration of remote sensing data with terrestrial bioecological observations

Conclusion

The study confirms the significant role of forest ecosystems in regulating the water balance and preventing soil degradation in Eastern Kazakhstan. The results show that forest soils retain 25-40% more moisture than steppe territories due to their higher organic matter content and well-developed root system. Coniferous forests demonstrate the greatest water retention capacity, followed by deciduous forests, while steppe soils are more susceptible to rapid drying and erosion.

Infiltration analysis shows that forest soils, especially in Markakolsky National Park and Bukhtarma forestry, have higher infiltration rates, which contributes to better groundwater replenishment. On the contrary, steppe soils exhibit a lower infiltration capacity, which leads to an increase in surface runoff and a higher risk of erosion. Soil evaporation rates also vary in different forest ecosystems, with Bukhtarma Forest District showing the highest levels of evaporation, and Markakol National Park the lowest, which highlights differences in microclimatic conditions and vegetation.

The assessment of erosion resistance shows that forest areas experience significantly lower rates of soil erosion compared to steppe zones. Coniferous forests with their dense vegetation and accumulated litter show the least erosion, while steppe areas suffer from severe soil loss due to

Spectral analysis of vegetation additionally confirms that forest landscapes support higher vegetation cover, which increases soil stability and reduces the risks of land degradation. Remote sensing data supports these findings, demonstrating that forests contribute to maintaining constant soil moisture levels and increasing ecosystem resilienceSpectral analysis of vegetation additionally confirms that forest landscapes support higher vegetation cover, which increases soil stability and reduces the risks of land degradation. Remote sensing data supports these findings, demonstrating that forests contribute to maintaining constant soil moisture levels and increasing ecosystem resilience. The highest NDVI values were recorded in Riddersky and Zyryanovsky forestry enterprises, indicating denser and healthier vegetation, while lower values in Markakolsky and Katon-Karagai National Parks indicate potential

Overall, the study highlights the important ecological function of forests in conserving water, preventing erosion, and maintaining land stability. Theall, the study highlights the important ecological function of forests in conserving water, preventing erosion, and maintaining land stability. The results highlight the need for sustainable forest management, afforestation

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СУ БАЛАНСЫН РЕТТЕУ ЖӘНЕ ТОПЫРАҚ ЭРОЗИЯСЫНАН ҚОРҒАУ ЖҮЙЕСІНДЕГІ ШЫҒЫС ҚАЗАҚСТАННЫҢ ОРМАН ЭКОЖҮЙЕЛЕРІ

Аңдатпа

Мақалада Шығыс Қазақстандағы орман экожүйелерінің су балансын реттеуге және топырақты деградациядан қорғауға әсері қарастырылған. Топырақтың суды ұстап тұру қабілетін, эрозия деңгейін және әртүрлі орман түзілімдеріндегі ылғалдылық динамикасын бағалау үшін эксперименттік зерттеулер жүргізілді. Нәтижелер ормандардың гидрологиялық режимді тұрақтандыруда және эрозия процестерінің алдын алуда маңызды рөл атқаратынын көрсетеді. Өсімдік жамылғысының тығыздығын, топырақ ылғалдылығының көрсеткіштерін және NDVI мәндерін талдау үшін қашықтықтан зондтау деректері мен ГАЖ технологиялары қолданылды, бұл экожүйелердің жай-күйін жан-жақты бағалауды қамтамасыз етеді. Зерттеу сонымен қатар эрозияға төзімділіктегі ағаштар мен бұталар құрамының рөлін зерттеп, аралас орман түзілімдерінің топырақ тұрақтылығын арттырудағы маңыздылығын көрсетеді. Нәтижелер жердің деградациясын азайту және аймақтық суды үнемдеу шараларын жақсарту үшін ормандарды басқарудың тұрақты тәжірибесі мен орман өсіру стратегияларының қажеттілігін көрсетеді. Жауын-шашынның инфильтрациясы мен булану жылдамдығын талдау ормандардың жер асты суларының тұрақты деңгейін ұстап тұруға, іргелес ауылшаруашылық және қалалық жерлерде құрғақшылық пен су тасқыны қаупін азайтуға ықпал ететінін көрсетеді. Зерттеу ормандарды сақтаудың адаптивті басқару стратегиялары, соның ішінде жергілікті түрлерді пайдалана отырып орман өсіру, бақыланатын жайылым әдістері және ландшафттардың тұрақтылығын арттыру үшін табиғи факторларға негізделген шешімдерді енгізу бойынша ұсыныстармен аяқталады. Бұл тұжырымдар Шығыс Қазақстан ормандарының экологиялық функцияларын сақтауға және ұзақ мерзімді экологиялық тұрақтылықты қамтамасыз етуге бағытталған кешенді саясатты әзірлеуге негіз болады.

Кілт сөздер: орман, су балансы, топырақ эрозиясы, топырақтың деградациясы, Шығыс Қазақстан.

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ЛЕСНЫЕ ЭКОСИСТЕМЫ ВОСТОЧНОГО КАЗАХСТАНА В СИСТЕМЕ РЕГУЛИРОВАНИЯ ВОДНОГО БАЛАНСА И ЗАЩИТЫ ПОЧВ ОТ ЭРОЗИИ

Аннотация

В статье рассматривается влияние лесных экосистем Восточного Казахстана на регулирование водного баланса и защиту почв от деградации. Были проведены экспериментальные исследования для оценки влагоудерживающей способности почв, уровня эрозии и динамики влажности в различных лесных формациях. Результаты показывают, что леса играют важную роль в стабилизации гидрологического режима и предотвращении процессов эрозии. Данные дистанционного зондирования и ГИС-технологии были использованы для анализа плотности растительного покрова, индексов влажности почвы и значений NDVI, что позволяет получить комплексную оценку состояния экосистемы. В исследовании также рассматривается роль состава деревьев и кустарников в устойчивости к эрозии, подчеркивается важность смешанных лесных формаций для повышения устойчивости почвы. Полученные результаты подчеркивают необходимость применения методов устойчивого лесопользования и стратегий облесения для смягчения последствий деградации земель и совершенствования региональных усилий по сохранению водных ресурсов. Анализ коэффициентов проникновения атмосферных осадков и суммарного испарения показывает, что леса способствуют поддержанию стабильного уровня грунтовых вод, снижая риск засух и наводнений в прилегающих сельскохозяйственных и городских районах. Исследование завершается рекомендациями по адаптивным стратегиям управления для сохранения лесов, включая облесение с использованием местных видов, методы контролируемого выпаса скота и внедрение решений, основанных на природных факторах, для повышения устойчивости ландшафтов. Эти выводы служат основой для разработки комплексной политики, направленной на сохранение экологических функций лесов в Восточном Казахстане и обеспечение долгосрочной экологической устойчивости.

Ключевые слова: лес, водный баланс, эрозия почв, деградация почв, Восточный Казахстан.

МРНТИ 68.47.75 **DOI** https://doi.org/10.37884/2-2025/49

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О ФОРМИРОВАНИИ ПРИРОДНО-ЭКОЛОГИЧЕСКОГО КАРКАСА ТЕРРИТОРИИ, КАК ПРОСТРАНСТВЕННО-ОРГАНИЗОВАННОЙ СТРУКТУРЫ УСТОЙЧИВОГО РАЗВИТИЯ РЕГИОНОВ КАЗАХСТАНА

Аннотация

В данной статье проведен системный анализ в области создания природно-экологического каркаса на основе изучения и анализа специальной литературы, нормативно-правовых документов, оценки природоохранной и рекреационной деятельности природоохранных учреждений, экосистемных услуг линейных лесонасаждений, водных ресурсов и др.