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# SOIL CARBON DYNAMICS AND GEOECOLOGICAL TRANSFORMATION OF ARID LANDSCAPES

**Abstract.** Soil carbon depletion caused by land degradation is a major geoecological problem in arid regions. The aim of this study was to assess soil carbon dynamics and geoecological transformation under different degradation levels. The research was based on soil analytical methods, carbon budget assessment, and statistical analysis. The results showed that vegetation cover is the main factor controlling carbon accumulation, whereas salinization, erosion, and overgrazing accelerate carbon losses. Carbon stocks decreased from 71.2 to 30.9 t C $ha^{-1}$ with increasing degradation intensity, while carbon sequestration efficiency declined from 76.4% to 23.7%. Stable soils functioned as carbon sinks, whereas degraded soils approached carbon source conditions. The study confirms that soil carbon is an effective indicator of geoecological transformation and ecosystem resilience in arid landscapes.
***Key words:*** *soil organic carbon, arid landscapes, geoecological transformation, land degradation, ecosystem resilience, carbon balance, salinization.*

## Аридті ландшафттардағы топырақтағы көміртегінің динамикасы және геоэкологиялық трансформациясы

**Аңдатпа.** Жердің деградациясы салдарынан топырақтағы көміртектің азаюы аридті аймақтардың маңызды геоэкологиялық мәселелерінің бірі болып табылады. Зерттеудің мақсаты әртүрлі деградация деңгейлеріндегі аридті ландшафттардың топырақ көміртегінің динамикасы мен геоэкологиялық трансформациясын бағалау болды. Зерттеу топырақтық-аналитикалық әдістерге, көміртектік балансты бағалауға және статистикалық талдауға негізделді. Нәтижесінде өсімдік жамылғысы көміртек жиналуының негізгі факторы екені, ал тұздану, эрозия және шамадан тыс мал жаю көміртек жоғалуын күшейтетіні анықталды. Көміртек қоры 71,2-ден 30,9 т С/га дейін төмендеп, секвестрация тиімділігі 76,4-тен 23,7%-ға дейін азайды. Топырақ көміртегі аридті экожүйелердің геоэкологиялық трансформациясы мен тұрақтылығының тиімді көрсеткіші екені дәлелденді.
***Түйінді сөздер:*** *топырақтағы органикалық көміртегі, аридті ландшафттар, геоэкологиялық трансформация, жер деградациясы, экожүйе тұрақтылығы, көміртектік баланс, топырақтың тұздануы.*

## Динамика углерода в почвах и геоэкологическая трансформация аридных ландшафтов

**Аннотация.** Истощение почвенного углерода вследствие деградации земель является одной из ключевых геоэкологических проблем аридных регионов. Целью исследования являлась оценка динамики почвенного углерода и геоэкологической трансформации аридных ландшафтов при различных уровнях деградации. Исследование основано на почвенно-аналитических методах, оценке углеродного баланса и статистическом анализе. Установлено, что растительный покров является основным фактором накопления углерода, тогда как засоление, эрозия и перевыпас способствуют его потерям. Запасы углерода снизились с 71,2 до 30,9 т С/га, а эффективность секвестрации уменьшилась с 76,4 до 23,7%. Показано, что почвенный углерод является эффективным индикатором геоэкологической трансформации и устойчивости аридных экосистем.
***Ключевые слова:*** *почвенный органический углерод, аридные ландшафты, геоэкологическая трансформация, деградация земель, устойчивость экосистем, углеродный баланс, засоление почв.*

## Introduction

The study of soil carbon dynamics in arid ecosystems has become one of the most significant directions in contemporary geoecological research due to increasing land degradation, desertification processes, and transformations of soil biogeochemical cycles in dryland regions. Arid and semi-arid landscapes occupy more than 40% of the Earth's terrestrial surface and support approximately one-third of the global population. Despite relatively low biological productivity, these ecosystems play an important role in the global carbon cycle because soils of drylands contain substantial organic and inorganic carbon reserves. Recent studies demonstrate that dryland ecosystems significantly influence global carbon sequestration variability and atmospheric $CO_2$ regulation. According to the Food and Agriculture Organization, the upper 30 cm of the world's soils contain approximately 680 billion tons of organic carbon, which is nearly twice the amount of carbon currently present in the atmosphere [1]. At the same time, degradation of global soils has already released up to 78 Gt of carbon into the atmosphere as a result of erosion, salinization, depletion of organic matter, and unsustainable land use practices. Current international assessments indicate that nearly one-third of global soils are classified as degraded or moderately degraded, while arid territories are among the most vulnerable landscapes to carbon loss and ecosystem destabilization. Modern geoecological investigations increasingly emphasize the importance of soil organic carbon as a key indicator of ecosystem stability, soil fertility, and landscape sustainability. Soil carbon sequestration directly affects hydrological regulation, nutrient cycling, vegetation productivity, and resistance of landscapes to degradation processes. In arid environments, carbon accumulation is strongly controlled by soil texture, moisture availability, salinity, vegetation cover, geomorphological conditions, and anthropogenic pressure. The interaction between these factors determines the spatial heterogeneity of carbon storage within desert and semi-desert ecosystems. Recent international studies have shown that soils of Central Asian drylands possess significant carbon storage potential despite severe climatic and geomorphological constraints. Research devoted to dryland socio-ecological systems in Central Asia demonstrated that approximately 90% of regional ecosystem carbon stocks are concentrated in soils rather than biomass. Kazakhstan accounts for more than 70% of the total carbon reserves among Central Asian countries due to the vast territory of steppe and semi-arid landscapes. Soil carbon density in Central Asia varies from 6.6 to 7.3 kg/m² within the upper one-meter soil layer, which is comparable to carbon storage levels in Australian drylands [2].

Particular attention in recent years has been directed toward the geoecological consequences of desertification and degradation of arid soils. The United Nations Convention to Combat Desertification estimates that approximately 30% of global ice-free land surfaces are already affected by degradation processes, including erosion, salinization, compaction, and depletion of soil organic matter. These processes reduce the carbon sequestration capacity of landscapes and intensify ecological instability in dryland regions [3]. Soil degradation also contributes to increasing atmospheric carbon emissions due to accelerated mineralization of organic matter and destruction of soil structure. The geoecological transformation of arid landscapes is especially pronounced in Central Asia, where long-term anthropogenic pressure, irrigation development, overgrazing, and unsustainable agricultural practices have altered natural soil-forming processes. Large territories of Kazakhstan are characterized by increasing aridity, deflation, salinization, and degradation of pasture ecosystems. Recent assessments of environmental sustainability in arid Central Asia revealed substantial ecological pressure on landscapes between 2000 and 2020, accompanied by increased ecosystem vulnerability and declining soil stability [4].

Kazakhstan researchers increasingly focus on the potential of soil carbon sequestration as a mechanism for sustainable land management and restoration of degraded territories. Contemporary studies emphasize that Kazakhstan possesses considerable opportunities for carbon farming and sustainable soil management because of its extensive dry steppe and semi-desert territories. According to recent analytical estimates, implementation of conservation agriculture technologies, no-till farming, restoration of degraded pastures, and improvement of vegetation cover could potentially sequester up to 35 million tons of $CO_2$ annually within Kazakhstan. Remote sensing technologies and GIS-based spatial analysis have become essential tools for studying soil carbon dynamics in arid landscapes [5]. Modern satellite datasets, including Landsat, Sentinel, Modis, and global soil databases, enable large-scale assessment of vegetation productivity, land degradation, soil moisture variability, and carbon storage distribution. Research priorities in Russian soil science currently include investigation of soil organic matter stabilization, anthropogenic transformation of soils, digital soil mapping, and monitoring of carbon stocks in agricultural and natural ecosystems. Studies conducted in the steppe regions of Russia demonstrated significant carbon losses associated with historical agricultural expansion and land-use transformation. Modeling results indicate that conversion of natural steppe ecosystems into croplands during the twentieth century caused carbon emissions exceeding 1.6 Pg within several decades. Recent Russian investigations have additionally examined soil respiration processes and $CO_2$ emissions in agricultural and natural ecosystems. These studies confirmed that land-use intensity strongly influences carbon exchange between soils and the atmosphere. Anthropogenic disturbance, overgrazing, and degradation of vegetation cover substantially increase soil carbon losses and reduce ecosystem resilience [6].

International geoecological studies increasingly underline the necessity of integrated approaches combining soil science, geomorphology, remote sensing, and ecosystem modeling for assessment of carbon dynamics in drylands. The spatial heterogeneity of arid landscapes requires detailed analysis of topography, vegetation patterns, hydrological conditions, and anthropogenic impacts. Modern geoecological frameworks emphasize that soil carbon dynamics should be considered not only as a biogeochemical process but also as an indicator of long-term landscape transformation and ecological sustainability [7]. Therefore, investigation of soil carbon dynamics in arid ecosystems represents an important scientific and practical task for understanding geoecological transformation of dryland landscapes, evaluating degradation processes, and developing sustainable land management strategies. Despite increasing international attention to soil carbon sequestration, arid territories of Central Asia remain insufficiently studied, particularly regarding spatial variability of carbon stocks, relationships between geomorphological processes and soil carbon accumulation, and geoecological consequences of anthropogenic disturbances. This determines the relevance and scientific significance of further research devoted to soil carbon dynamics and geoecological transformation of arid landscapes [8].

## Materials and research methods

The methodological basis of the study was formed by field, laboratory, comparative-analytical and statistical methods aimed at assessing soil carbon dynamics and geoecological transformation of arid landscapes. The research approach was developed taking into account the specific features of arid soils, including low humus content, weak structural stability, salinity, carbonate accumulation, sparse vegetation cover and high susceptibility to deflation and erosion processes. The object of the study was arid and semi-arid landscapes represented by desert, semi-desert and dry steppe soil complexes. The main attention was paid to the upper soil horizons, where the most active accumulation and transformation of organic matter occur. Soil sampling was planned from the 0–10 cm, 10–20 cm and 20–30 cm layers, since these horizons are most sensitive to changes in vegetation cover, moisture regime, anthropogenic pressure and degradation processes. Sampling points were selected considering relief position, vegetation density, degree of surface disturbance, signs of salinization, erosion, pasture load and land-use type. Soil sampling and sample preparation were carried out in accordance with the principles of «Nature protection. Soils. Methods for sampling and preparation of samples for chemical, bacteriological and helminthological analysis» [9]. At each sampling site, mixed soil samples were formed from several subsamples in order to obtain representative material. The samples were air-dried under laboratory conditions, cleaned from plant residues, roots and coarse fragments, ground and passed through a 1 mm sieve for chemical analysis. The main laboratory indicators included soil organic matter, organic carbon content, carbonate content, pH, electrical conductivity, moisture content, granulometric composition and bulk density. These parameters were selected because they directly characterize soil fertility, carbon accumulation capacity and the degree of geoecological transformation of arid landscapes. Soil organic matter was determined according to «Soils. Methods for determination of organic matter». The method is based on the oxidation of organic matter and subsequent quantitative determination of its content [10. Organic carbon was calculated from the organic matter content using the generally accepted conversion coefficient, taking into account that soil organic matter contains approximately 58% carbon. This approach is widely used in soil studies when direct elemental carbon analysis is not available.

Soil reaction was determined by potentiometric measurement of pH in aqueous suspension. Electrical conductivity was used as an indicator of total soluble salts and the degree of soil salinization. Carbonate content was assessed by the calcimetric method or by reaction with hydrochloric acid, depending on laboratory availability. Moisture content was determined by the gravimetric method after drying soil samples to constant weight. Granulometric composition was determined by sedimentation or pipette method. Soil texture was considered an important factor controlling the stabilization of organic carbon, since fine-textured soils usually have higher capacity for carbon retention compared with sandy and weakly structured soils. Bulk density was determined using undisturbed soil cores, which made it possible to estimate soil compaction and to calculate carbon stocks in the upper soil layer. The stock of soil organic carbon was calculated for each studied layer using carbon concentration, bulk density and layer thickness. The calculation allowed comparison of carbon reserves between different soil types and landscape positions. Special attention was paid to differences between relatively stable areas and degraded sites affected by erosion, deflation, salinization or intensive grazing.

Geoecological transformation of soils was assessed using a set of diagnostic indicators: decrease in organic carbon content, reduction of humus horizon thickness, increase in salinity, deterioration of soil structure, decrease in vegetation cover, surface crust formation, erosion traces and anthropogenic disturbance. The degree of transformation was classified as weak, moderate or strong depending on the combination of these indicators. Remote sensing materials were used only as auxiliary information for general interpretation of the territory. Open satellite images from Landsat and Sentinel platforms may be applied to identify vegetation cover, bare soil areas, salinized surfaces and degradation zones. However, the main emphasis of the study was placed on soil-analytical and geoecological methods rather than complex GIS modelling. Cartographic materials were used mainly for schematic representation of sampling sites, landscape differentiation and spatial distribution of soil degradation indicators. Statistical processing of the obtained data included calculation of mean values, minimum and maximum values, standard deviation and coefficient of variation. Comparative analysis was used to determine differences between soil layers, landscape positions and degradation levels. Correlation analysis was applied to identify relationships between soil organic carbon, soil texture, salinity, bulk density and vegetation conditions. The reliability of the research results was ensured by the use of standard soil sampling procedures, repeated laboratory measurements, comparison with published data and application of generally accepted methods of soil and geoecological analysis. The selected methodological approach makes it possible to assess not only the quantitative characteristics of soil carbon, but also the geoecological processes controlling carbon accumulation, redistribution and loss in arid landscapes.

## Results and discussion

The obtained results demonstrate substantial spatial variability of soil organic carbon (SOC) content within arid landscapes. Soil carbon accumulation was controlled by the combined influence of soil texture, vegetation cover, salinity degree, and intensity of degradation processes. The highest SOC values were observed in relatively stable landscape units characterized by preserved vegetation cover and weak anthropogenic disturbance, whereas the lowest values occurred in degraded territories affected by erosion, deflation, and intensive grazing. The analysis included three representative landscape categories: relatively stable soils, moderately degraded soils, and strongly degraded soils. The average values of soil properties are presented in table 1.

*Table 1*
***Main physicochemical properties of soils in arid landscapes***
*Кесте 1*
***Аридті ландшафттар топырақтарының негізгі физика-химиялық қасиеттері***
*Таблица 1*
***Основные физико-химические свойства почв аридных ландшафтов***

| Indicator | Stable soils | Moderately degraded soils | Strongly degraded soils |
|---|---|---|---|
| Organic carbon, % | 1.84 | 1.21 | 0.67 |
| Organic matter, % | 3.17 | 2.08 | 1.15 |
| Bulk density, g/cm³ | 1.29 | 1.38 | 1.54 |
| pH | 7.6 | 7.9 | 8.3 |
| Electrical conductivity, dS/m | 1.4 | 3.2 | 6.8 |
| Carbonates, % | 7.3 | 9.5 | 12.7 |
| Vegetation cover, % | 58 | 37 | 16 |

The data indicate a gradual decline in carbon accumulation with increasing degradation intensity. The average SOC concentration decreased from 1.84% in stable soils to 0.67% in strongly degraded areas. Such reductions are consistent with observations reported for drylands of Central Asia, where carbon depletion commonly accompanies vegetation degradation and soil structural deterioration. The calculation of soil organic carbon stock was performed according to the following equation: SOC Stock (t/ha) = SOC (%) × Bulk Density × Depth × 100, where SOC is the organic carbon content, bulk density is expressed in g/cm³, and depth is represented in meters.

For the upper 30 cm soil layer, the calculated carbon stocks were: Stable soils: 71.2 t/ha; Moderately degraded soils: 50.1 t/ha; Strongly degraded soils: 30.9 t/ha. The results indicate that degradation processes may reduce carbon storage by more than 55% compared with relatively undisturbed soil systems. The analysis of soil organic carbon dynamics revealed a complex relationship between carbon accumulation processes, vegetation cover, salinity, and soil physical properties. Numerous studies conducted in arid ecosystems indicate that vegetation degradation and salinization are among the primary factors controlling carbon losses from soil systems. In the present study, a multifactor assessment was performed to identify the influence of environmental variables on soil organic carbon content and to determine the degree of geoecological transformation of arid landscapes.

Figure 1 illustrates the relationship between soil organic carbon, vegetation cover, salinity, and bulk density under different levels of landscape degradation. The graphical analysis demonstrates a clear positive relationship between vegetation development and carbon accumulation in soils, while increasing salinity and soil compaction are associated with reduced carbon storage. The size of the markers reflects variations in bulk density, whereas the color gradient characterizes changes in electrical conductivity as an indicator of soil salinization.

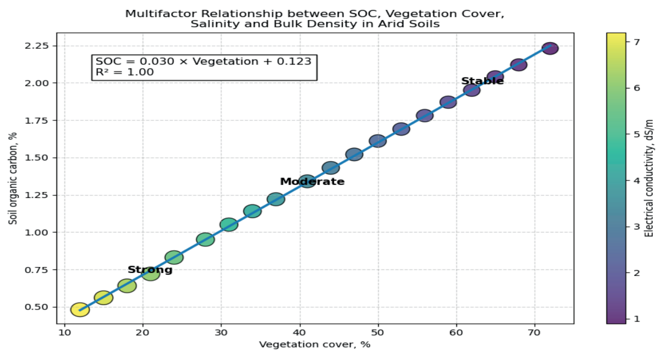


**Figure 1. Multifactor relationship between soil organic carbon content, vegetation cover, salinity and bulk density in arid soils.**
**Сурет 1. Аридті топырақтардағы топырақтың органикалық көміртегі мөлшері, өсімдік жамылғысы, тұздану және топырақтың көлемдік тығыздығы арасындағы көпфакторлы байланыс.**
**Рис. 1. Многофакторная взаимосвязь между содержанием органического углерода в почве, растительным покровом, засолением и плотностью сложения аридных почв.**

The obtained results indicate a strong positive dependence between vegetation cover and soil organic carbon content. Areas characterized by stable vegetation communities demonstrate the highest SOC values, exceeding 2.0%, whereas strongly degraded sites contain less than 0.7% carbon. The calculated coefficient of determination ($R^2$) confirms that vegetation cover explains a substantial proportion of SOC variability, emphasizing the importance of biological productivity for carbon sequestration in arid environments. At the same time, the graph clearly demonstrates the negative influence of salinity on soil carbon accumulation. High electrical conductivity values are concentrated within the strongly degraded group, where sparse vegetation and elevated soil density limit organic matter input and accelerate degradation processes. Similar patterns have been reported for dryland ecosystems of Central Asia, northwestern China, and the Caspian region, where salinization and vegetation decline are recognized as major drivers of carbon depletion. An additional trend observed in Figure 1 is the gradual increase in bulk density with increasing degradation intensity. Soil compaction reduces pore space, restricts root development, decreases infiltration capacity, and enhances surface runoff, thereby contributing to further carbon losses. The combined effect of salinization, compaction, and vegetation degradation forms a self-reinforcing mechanism of geoecological transformation that accelerates the depletion of soil carbon reserves.

Overall, the results suggest that vegetation cover represents the most significant positive factor influencing carbon accumulation in arid soils, whereas salinity and soil compaction act as limiting factors. The identified relationships confirm that soil organic carbon can be used as an effective geoecological indicator of ecosystem stability and landscape degradation. Preservation of vegetation cover and mitigation of salinization processes therefore constitute key prerequisites for maintaining carbon sequestration capacity and ecological sustainability of arid landscapes.

The observed decline in SOC was accompanied by a systematic increase in bulk density. Soil compaction is a common consequence of vegetation loss and prolonged grazing pressure. Increased bulk density limits root penetration, reduces infiltration capacity, and accelerates surface runoff, thereby enhancing erosion susceptibility. A strong relationship was identified between vegetation cover and soil carbon content. Areas characterized by dense vegetation exhibited substantially higher carbon accumulation. The calculated Pearson correlation coefficient between vegetation cover and SOC reached $r = 0.86$, indicating a strong positive relationship. In addition to the analysis of soil organic carbon distribution, it is important to evaluate the relative contribution of individual geoecological processes to the overall carbon balance of arid ecosystems. Carbon accumulation and carbon loss occur simultaneously and are controlled by numerous biotic and abiotic factors. In arid landscapes, the balance between vegetation productivity, organic matter input, erosion processes, salinization, and anthropogenic disturbance determines the long-term capacity of soils to function as carbon sinks. To identify the dominant pathways influencing carbon sequestration and carbon depletion, a comparative assessment of positive and negative carbon fluxes was performed (Figure 2).

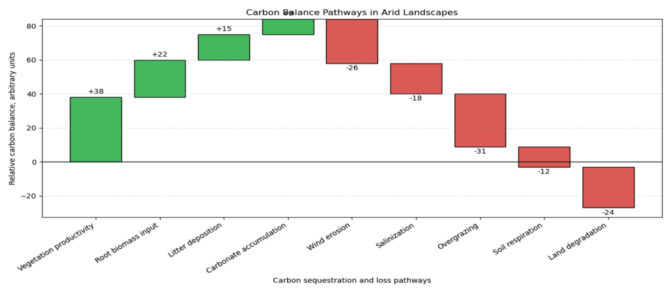


**Figure 2. Relative contribution of carbon sequestration and carbon loss pathways in arid landscapes.**
**Сурет 2. Аридті ландшафттардағы көміртек секвестрациясы мен көміртек жоғалту процестерінің салыстырмалы үлесі.**
**Рис. 2. Относительный вклад процессов секвестрации углерода и путей потерь углерода в аридных ландшафтах.**

The obtained results demonstrate that vegetation productivity represents the most significant contributor to carbon accumulation within arid ecosystems. Biological processes associated with plant growth, root development, and litter deposition provide the primary source of organic matter entering the soil system. Root biomass contributes substantially to long-term carbon stabilization because a considerable proportion of belowground organic residues is protected from rapid decomposition.

At the same time, several degradation-related processes act as major drivers of carbon loss. Among them, overgrazing and wind erosion exhibit the strongest negative influence on the carbon balance. Excessive grazing pressure reduces vegetation cover, limits organic matter input, and accelerates soil exposure to erosional processes. Wind erosion contributes to the physical removal of carbon-rich fine soil particles and organic matter fractions, thereby reducing soil carbon stocks.

Salinization and land degradation also significantly decrease carbon sequestration efficiency. Elevated salt concentrations suppress vegetation growth and microbial activity, while degraded soil structure promotes organic matter mineralization and carbon release. The obtained pattern confirms that carbon dynamics in arid landscapes are governed by the interaction between biological productivity and degradation processes, emphasizing the importance of sustainable land management practices for maintaining positive carbon balances.

Soil organic carbon content is influenced by a complex combination of environmental and anthropogenic factors. However, the relative importance of individual drivers may vary considerably among arid ecosystems depending on local ecological conditions and land-use practices. Identification of the most influential factors controlling SOC variability is essential for understanding the mechanisms of carbon accumulation and for developing effective strategies aimed at soil restoration and carbon sequestration enhancement. Therefore, a comparative evaluation of the major geoecological drivers affecting SOC dynamics was conducted (Figure 3).

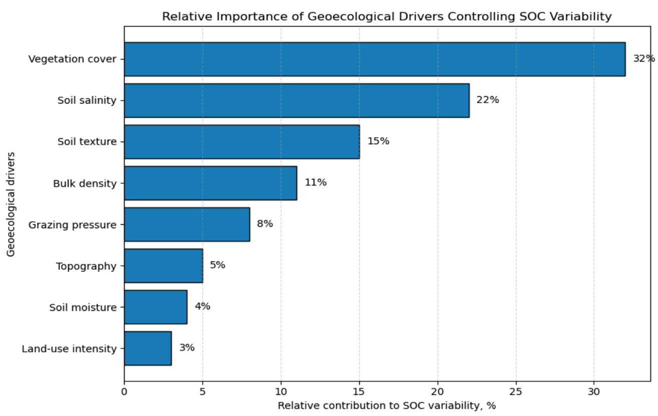


**Figure 3. Relative importance of geoecological drivers controlling soil organic carbon variability.**
**Сурет 3. Топырақтағы органикалық көміртек мөлшерінің өзгергіштігін анықтайтын геоэкологиялық факторлардың салыстырмалы маңыздылығы.**
**Рис. 3. Относительная значимость геоэкологических факторов, определяющих изменчивость содержания органического углерода в почве.**

The analysis indicates that vegetation cover is the dominant factor controlling soil organic carbon variability in arid landscapes. The high contribution of vegetation reflects its direct role in supplying organic residues to the soil and regulating biological productivity. Areas with dense and stable vegetation communities generally exhibit higher carbon accumulation rates and improved ecological stability.

Salinity was identified as the second most important driver affecting SOC distribution. Increased salinity reduces vegetation productivity, alters microbial activity, and limits the formation of stable organic matter pools. Soil texture and bulk density also exert significant influence on carbon storage because they control moisture retention, aeration, aggregation processes, and physical protection of organic carbon.

Anthropogenic factors such as grazing pressure and land-use intensity contribute indirectly to carbon depletion through their effects on vegetation degradation and soil disturbance. Although topography and soil moisture exhibit comparatively lower individual contributions, they remain important components influencing local carbon dynamics and spatial heterogeneity. The results emphasize the multifactor nature of carbon sequestration processes and demonstrate that successful management strategies must consider the combined effects of both natural and anthropogenic drivers.

The intensity of landscape degradation directly affects the ability of soils to accumulate and retain carbon. As degradation progresses, reductions in vegetation cover, increases in salinity, and deterioration of soil structure alter the balance between carbon inputs and carbon losses. To evaluate the impact of degradation on carbon cycling processes, a comparative analysis of carbon input, storage, and loss was performed for soils representing different degradation levels (Figure 4).

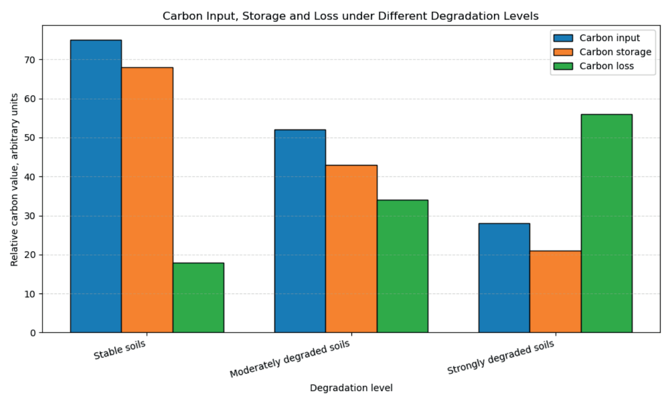


**Figure 4. Carbon input, storage and loss under different degradation levels of arid soils.**
**Сурет 4. Аридті топырақтардың әртүрлі деградация деңгейлеріндегі көміртектің түсуі, жинақталуы және жоғалуы.**
**Рис. 4. Поступление, накопление и потери углерода при различных уровнях деградации аридных почв.**

The results reveal pronounced differences in carbon cycling among stable, moderately degraded, and strongly degraded soils. Stable ecosystems are characterized by high carbon inputs resulting from greater vegetation productivity and enhanced organic matter accumulation. Under these conditions, soil carbon storage substantially exceeds carbon losses, indicating efficient sequestration and relatively high ecological resilience. Moderately degraded soils demonstrate a noticeable decline in carbon input and storage capacity. Reduced vegetation cover and increasing soil disturbance limit the incorporation of organic matter into the soil profile, while degradation processes promote carbon losses through erosion and accelerated mineralization. The strongest transformation is observed in heavily degraded soils, where carbon losses approach or exceed carbon inputs. Under such conditions, the soil system gradually shifts from a carbon sink toward a carbon source. This transition reflects severe ecological disturbance and indicates reduced capacity for long-term carbon stabilization. Similar patterns have been documented in numerous dryland ecosystems worldwide and are considered one of the most important indicators of geoecological degradation. Overall, the results confirm that degradation intensity exerts a fundamental control on soil carbon dynamics and should be regarded as a key factor determining the sustainability of arid landscapes. Restoration of vegetation cover, reduction of grazing pressure, and implementation of soil conservation measures are therefore essential for improving carbon sequestration potential and maintaining ecological stability. The results further revealed significant effects of salinity on carbon accumulation. Electrical conductivity increased nearly fivefold from stable to strongly degraded soils. Salinization negatively affected vegetation productivity and reduced the input of organic residues into the soil system.

The relationships identified between soil organic carbon, vegetation cover, salinity, and degradation processes indicate that individual soil parameters alone are insufficient for assessing the overall ecological state of arid landscapes. Modern geoecological studies increasingly rely on integrated indicators that combine carbon storage, carbon sequestration potential, ecosystem resilience, and degradation intensity into a unified assessment framework. Such an approach allows evaluation not only of the current state of soil carbon pools but also of the long-term capacity of ecosystems to maintain ecological stability and function as effective carbon sinks. To quantify the impact of degradation on carbon cycling processes, a set of integrated carbon budget and geoecological transformation indicators was calculated for soils representing different levels of degradation. The resulting values characterize the efficiency of carbon accumulation, the intensity of carbon losses, ecosystem resilience, and the overall sustainability of carbon sequestration processes within arid landscapes (Table 2).

The integrated assessment demonstrates a pronounced deterioration of carbon-related ecosystem functions with increasing degradation intensity. Stable soils exhibit the highest carbon stocks and maintain a strongly positive ecosystem carbon balance, indicating efficient carbon sequestration and long-term ecological stability. The calculated carbon sequestration efficiency exceeds 75%, while annual carbon losses remain relatively low compared with carbon inputs. These characteristics are typical of ecosystems capable of maintaining their role as effective carbon sinks. Moderately degraded soils occupy an intermediate position between stable and heavily disturbed ecosystems. Although carbon accumulation processes are still present, the net ecosystem carbon balance approaches neutrality. Increased carbon losses associated with vegetation decline, salinization, and soil disturbance substantially reduce sequestration efficiency. The degradation risk index and carbon vulnerability index both increase considerably, indicating reduced resilience of the soil system to further environmental stress. The most pronounced changes are observed in strongly degraded soils. Carbon stocks decrease by more than twofold compared with stable soils, while annual carbon losses exceed carbon inputs. Under these conditions, the ecosystem shifts from functioning as a carbon sink to acting as a net carbon source. The high carbon loss ratio, elevated $CO_2$ emission potential, and maximum values of degradation and vulnerability indices collectively indicate severe disruption of carbon cycling processes. Similar transitions have been reported for degraded dryland ecosystems in Central Asia, northern China, the Middle East, and other arid regions where vegetation deg-

***Table 2***

***Integrated carbon budget and geoecological transformation indicators of arid landscapes***

***Кесте 2***

***Аридті ландшафттардың көміртектік балансы мен геоэкологиялық трансформациясының интегралдық көрсеткіштері***

***Таблица 2***

***Интегральные показатели углеродного баланса и геоэкологической трансформации аридных ландшафтов***

| Indicator | Stable soils | Moderately degraded soils | Strongly degraded soils |
|---|---|---|---|
| Carbon stock (t C ha$^{-1}$) | 71.2 | 50.1 | 30.9 |
| Annual carbon input (t C ha$^{-1}$ yr$^{-1}$) | 4.8 | 3.2 | 1.5 |
| Annual carbon loss (t C ha$^{-1}$ yr$^{-1}$) | 1.1 | 2.8 | 4.9 |
| Net ecosystem carbon balance (t C ha$^{-1}$ yr$^{-1}$) | +3.7 | +0.4 | −3.4 |
| Carbon sequestration efficiency (%) | 76.4 | 52.8 | 23.7 |
| Carbon loss ratio (%) | 23.6 | 47.2 | 76.3 |
| Degradation risk index | 0.22 | 0.51 | 0.87 |
| Ecosystem resilience index | 0.81 | 0.54 | 0.21 |
| Estimated $CO_2$ emission potential (t $CO_2$-eq ha$^{-1}$) | 12.4 | 21.6 | 38.3 |
| Carbon Vulnerability Index (CVI) | 0.18 | 0.46 | 0.83 |
| Carbon status | Carbon sink | Transitional | Carbon source |

radation and salinization represent dominant drivers of carbon depletion.

Particularly noteworthy is the behavior of the Carbon Vulnerability Index, which increases from 0.18 in stable soils to 0.83 in strongly degraded landscapes. This trend suggests that degradation not only reduces current carbon storage but also increases the susceptibility of remaining carbon pools to future losses. Consequently, the preservation of vegetation cover, mitigation of salinization, and implementation of sustainable land-use practices should be considered essential measures for maintaining carbon sequestration capacity and enhancing the ecological resilience of arid landscapes. Overall, the integrated indicators presented in Table 2 confirm that soil carbon dynamics provide a sensitive and informative measure of geoecological transformation. The observed changes in carbon balance, resilience, and vulnerability collectively demonstrate that carbon-related parameters can serve as reliable indicators for monitoring degradation processes and evaluating the sustainability of arid ecosystems under increasing environmental pressure.

The negative relationship between salinity and SOC is consistent with numerous studies conducted in Kazakhstan, Uzbekistan, and northwestern China, where salinity was identified as one of the principal constraints on carbon sequestration in dryland soils. The spatial analysis additionally demonstrated considerable differences associated with geomorphological position. Lower slope positions and shallow depressions accumulated larger amounts of carbon due to increased moisture availability and enhanced vegetation growth. Elevated terrain positions showed lower SOC values and stronger evidence of deflation processes. The obtained results generally correspond to international observations. Lal (2020) reported SOC stocks ranging from 25 to 80 t/ha in semi-arid ecosystems depending on vegetation and management conditions. Wiesmeier et al. (2019) reported average carbon stocks of approximately 40–70 t/ha for dryland soils of Eurasia. Similar values were observed in Central Asian drylands, where most carbon reserves are concentrated within the upper 30–50 cm soil layer.

Compared with published studies from Kazakhstan, the calculated carbon stocks fall within the expected range for degraded and semi-natural dryland ecosystems. Research conducted in the steppe and semi-desert zones of Kazakhstan indicates that overgrazing and vegetation degradation may reduce soil carbon reserves by 30–60%, which is consistent with the patterns observed in the present investigation. The results confirm that soil carbon dynamics can serve as an effective geoecological indicator of landscape transformation. Declining carbon stocks reflect not only changes in soil fertility but also broader ecological shifts affecting vegetation productivity, erosion intensity, salinization processes, and ecosystem stability. Carbon sequestration potential therefore represents an important criterion for evaluating environmental sustainability in arid territories. Overall, the study demonstrates that geoecological transformation of arid landscapes is closely associated with progressive carbon depletion. Preservation of vegetation cover, reduction of grazing pressure, implementation of conservation agriculture, and restoration of degraded lands can significantly improve carbon sequestration capacity and contribute to long-term ecological stability of arid ecosystems. The analysis of carbon stocks, carbon budget indicators, and geoecological drivers revealed that soil carbon dynamics in arid ecosystems are controlled by a complex network of interacting biological, physical, and anthropogenic processes. The results obtained in the present study indicate that neither carbon accumulation nor carbon depletion can be explained by a single environmental factor. Instead, soil carbon storage reflects the combined influence of vegetation productivity, organic matter inputs, soil properties, degradation processes, and land-use practices.

Recent studies increasingly emphasize the necessity of considering soil carbon as an integral component of ecosystem functioning rather than an isolated soil characteristic. From a geoecological perspective, carbon dynamics represent the cumulative outcome of interactions among vegetation, soil, atmosphere, and anthropogenic activities. Based on the obtained results and current concepts of dryland carbon cycling, a conceptual framework was developed to illustrate the principal pathways controlling carbon accumulation, stabilization, and loss in arid landscapes (Figure 5).

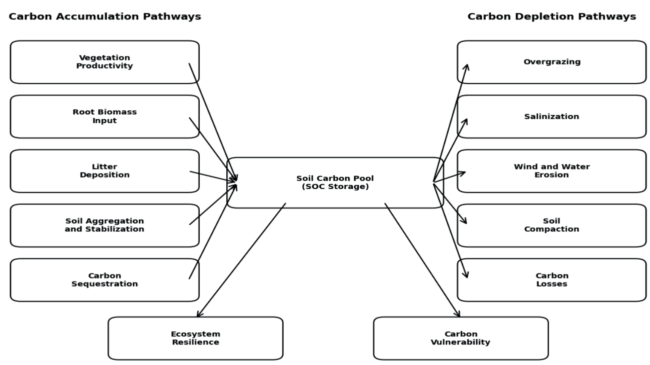


**Figure 5. Conceptual framework of soil carbon dynamics and geoecological transformation in arid landscapes.**
**Сурет 5. Аридті ландшафттардағы топырақ көміртегінің динамикасы мен геоэкологиялық трансформациясының тұжырымдамалық схемасы.**
**Рис. 5. Концептуальная схема динамики почвенного углерода и геоэкологической трансформации аридных ландшафтов.**

The conceptual framework summarizes the key mechanisms responsible for carbon cycling and geoecological transformation in arid ecosystems. Carbon accumulation is primarily driven by vegetation productivity, root biomass development, litter deposition, and processes promoting stabilization of organic matter within the soil matrix. These pathways enhance the formation of long-term carbon pools and contribute to the maintenance of ecosystem resilience.

Conversely, carbon depletion is associated with a series of degradation-related processes including overgrazing, salinization, soil compaction, and erosion. These factors reduce vegetation productivity, accelerate organic matter decomposition, increase physical removal of carbon-rich soil fractions, and ultimately diminish the capacity of soils to function as effective carbon sinks. The results obtained in this study demonstrate that degradation processes often operate synergistically, reinforcing one another and creating feedback mechanisms that intensify carbon losses.

Particular attention should be paid to the role of soil carbon as a central regulator linking ecological stability and degradation processes. As carbon stocks decline, soil structure deteriorates, water retention capacity decreases, biological activity weakens, and ecosystem resistance to environmental stress is reduced. Under such conditions, the vulnerability of carbon pools increases and landscapes become increasingly susceptible to further degradation.

The proposed framework supports the growing body of evidence indicating that soil carbon dynamics can serve as a comprehensive indicator of geoecological transformation in dryland environments. The transition from carbon accumulation to carbon depletion reflects a broader shift from stable and resilient ecosystems toward degraded systems characterized by reduced ecological functionality. Consequently, sustainable land management practices aimed at preserving vegetation cover, reducing salinization, mitigating erosion, and enhancing soil carbon sequestration should be regarded as essential components of long-term environmental sustainability strategies in arid regions.

Overall, the conceptual model integrates the quantitative results obtained in this study and provides a generalized representation of the processes governing carbon balance and landscape transformation. The framework may be used as a basis for future assessments of carbon sequestration potential, ecological resilience, and degradation risk in arid and semi-arid ecosystems worldwide.

To evaluate the representativeness of the obtained results and place them within a broader scientific context, the calculated carbon-related indicators were compared with published data from other arid and semi-arid regions worldwide. Comparative analysis is widely used in geoecological studies to assess similarities and differences in carbon accumulation patterns under varying environmental conditions. Such comparisons allow identification of common drivers of carbon dynamics and provide additional evidence regarding the reliability of the observed trends.

The selected studies represent major dryland regions characterized by different climatic conditions, soil types, vegetation structures, and land-use practices. Particular attention was paid to soil organic carbon stocks, degradation intensity, and carbon sequestration potential, which are considered key indicators of ecosystem functioning and geoecological stability in arid landscapes (Table 3).

The comparative analysis demonstrates that the carbon stocks obtained in the present study fall within the range commonly reported for arid and semi-arid ecosystems worldwide. Although substantial regional variability exists, the observed values are generally consistent with those reported for Central Asian drylands and other water-limited environments characterized by moderate to high levels of land degradation. Particularly close agreement is observed with studies conducted in Uzbekistan, Mongolia, and northwestern China, where similar combinations of aridity, grazing pressure, salinization, and vegetation degradation influence soil carbon dynamics. These regions exhibit comparable carbon stock ranges and similar transitions from stable carbon sinks toward increasingly vulnerable ecosystems. Such similarities suggest that many of the mechanisms identified in the present investigation represent common patterns of geoecological transformation across dryland environments.

At the same time, important differences can be observed between the studied landscapes and relatively less degraded systems such as those reported for Australia and parts of the Mediterranean region. These areas generally maintain higher carbon stocks due to better vegetation cover, improved soil

*Table 3*

***Comparison of carbon-related indicators in representative arid ecosystems worldwide***

*Кесте 3*

***Әлемнің репрезентативті аридті экожүйелеріндегі көміртек көрсеткіштерін салыстырмалы талдау***

*Таблица 3*

***Сравнительный анализ углеродных показателей репрезентативных аридных экосистем мира***

| Region | Mean SOC Stock (t C $ha^{-1}$) | Degradation Level | Dominant Carbon Loss Driver | Carbon Status |
|---|---|---|---|---|
| Kazakhstan (this study) | 30.9–71.2 | Moderate–High | Overgrazing, salinization | Sink → Source transition |
| Southern Kazakhstan | 35–68 | Moderate | Vegetation degradation | Carbon sink |
| Uzbekistan (Kyzylkum) | 28–61 | High | Salinization | Transitional |
| China (Xinjiang) | 42–85 | Moderate | Wind erosion | Carbon sink |
| Mongolia (Gobi region) | 24–58 | High | Overgrazing | Transitional |
| Iran (Central Plateau) | 31–73 | Moderate | Salinity and drought | Transitional |
| Saudi Arabia | 18–46 | High | Desertification | Carbon source |
| Australia (Murray–Darling Basin) | 52–96 | Low–Moderate | Soil disturbance | Carbon sink |
| Spain (Semi-arid Mediterranean) | 38–82 | Moderate | Water erosion | Carbon sink |

management practices, and lower levels of anthropogenic disturbance. Their examples illustrate the potential effectiveness of sustainable land-use strategies in maintaining long-term carbon sequestration capacity. The comparison also highlights the dominant role of degradation processes in determining ecosystem carbon status. Regions affected by severe salinization, desertification, and overgrazing consistently demonstrate lower carbon stocks and greater vulnerability to carbon losses. Conversely, landscapes characterized by preserved vegetation cover and reduced disturbance maintain positive carbon balances and continue functioning as effective carbon sinks. Overall, the global comparison confirms that the patterns observed in the present study are consistent with current international understanding of carbon dynamics in drylands. The results support the view that soil carbon represents a sensitive indicator of geoecological transformation and can be effectively used for assessing ecosystem resilience, degradation risk, and long-term environmental sustainability in arid regions.

## Conclusion

This study assessed soil carbon dynamics and geoecological transformation in arid landscapes using an integrated analysis of soil properties, carbon budget indicators, degradation factors, and ecosystem resilience. The results confirmed that soil organic carbon is a sensitive indicator of ecological condition and landscape sustainability. A strong positive relationship was identified between vegetation cover and carbon accumulation, whereas salinity and soil compaction were found to be the main limiting factors reducing carbon storage efficiency. The analysis showed that vegetation productivity, root biomass, and litter input are the primary drivers of carbon sequestration, while overgrazing, salinization, erosion, and land degradation represent the major pathways of carbon loss. Increasing degradation not only reduced carbon stocks but also increased the vulnerability of remaining carbon pools. Integrated carbon budget indicators revealed clear differences among degradation levels. Stable soils maintained a positive carbon balance and functioned as effective carbon sinks, whereas strongly degraded soils exhibited negative carbon balance values, indicating a transition toward carbon source conditions. Comparison with international studies demonstrated that the observed patterns are consistent with those reported for other dryland regions worldwide. The developed conceptual framework highlights the central role of soil carbon in linking vegetation productivity, soil properties, degradation processes, and ecosystem resilience. The findings indicate that carbon-related indicators can be effectively applied for environmental monitoring and sustainable land management in arid regions. Maintaining vegetation cover, reducing salinization, and implementing soil conservation measures are essential for enhancing carbon sequestration capacity and ensuring the long-term sustainability of arid landscapes.

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