LANDSCAPE AND ECOLOGICAL CONDITIONS OF CARBON SEDIMENTATION IN MOUNTAIN-MEADWAY LANDSCAPES OF THE CHECHEN REPUBLIC

Rustam Gakaev, Nadir Gadjiev, Ibragim Isaev

•

Kadyrov Chechen State University, RUSSIA
rustam.geofak@yandex.ru
muslimjkl@mail.ru
nadirgadji@mail.ru

Abstract

Carbon sequestration and dynamics in mountain meadow landscapes through photosynthesis are crucial for the survival of the biosphere. The role of soil in forest ecosystems is largely determined by its organic compounds. Carbon compounds largely determine soil formation. Soil organic matter is a source of energy for soil organisms, which, in turn, interact with the mineral component of the soil to shape its structure. Soil carbon plays a significant role in nutrient cycling. Consequently, the quantity and quality of soil organic matter reflect and determine its formation and, consequently, the productivity of forest ecosystems. Landscape-ecological conditions for carbon dynamics are examined at the regional level. Phytoclimatic, altitudinal, zonal, and aspect differentiation in terms of carbon dynamics are revealed. A comparative analysis of carbon dynamics conditions in different landscape types is provided, and the effectiveness of various ecosystems in terms of carbon accumulation is assessed. Specifically, carbon dynamics are compared in mountain forest, mountain meadow, and mountain meadow-steppe landscapes. Due to climate warming, mountain meadow landscapes are beginning to expand into areas free of snow and ice. Therefore, they can be considered important carbon sequestration sites.

Keywords: Mortmass, biomass, landscape differentiation, carbon sequestration, mountainous areas, soil types, accumulation, humus.

I. Introduction

The theoretical basis for studying the diversity of carbon balance conditions is the landscape concept, which views mountainous areas as a systemically organized space of ecological-landscape habitats, each representing a relatively homogeneous area in which the components of the carbon balance are approximately equal. The concept of landscape structure underlies the extrapolation of the obtained data on carbon dynamics in a specific natural complex. Three main types of landscape structure are distinguished, corresponding to landscape responses to the impacts and changes in energy fields: vertical, horizontal (morphological), and temporal.

One of the fundamental patterns of landscape spatial organization is altitudinal zonation. Altitude zones are defined by the predominant zonal landscape type, and belts within them are defined by landscape subtype. However, the distribution of landscape types and the ratio of their areas is uneven within the study area of the Chechen Republic. Classical altitudinal belts that uniformly and consistently change with altitude are virtually absent. Their boundaries are uneven due to the complex mountainous terrain and/or anthropogenic impact.

The leading factor in altitudinal differentiation is the change in the heat-to-moisture ratio with altitude. The greatest variation is the change in heat with altitude. Different landscape types are formed at different altitudinal levels: nival-glacial landscapes – above 3000-3500 m above sea level;

mountain-meadow landscapes – the lower boundary varies from 2000 to 2500 m, and the upper boundary coincides with the lower boundary of nival-glacial landscapes, i.e., 3000-3500 m above sea level; mountain-forest landscapes extend to an altitude of 2000 m, and in some areas of warm slopes – up to 2600 m; Mountain forest-meadow, mountain forest-meadow-steppe, and mountain steppe – from 250 to 1800-2400 m.

According to the Intergovernmental Panel on Climate Change (IPCC) (2000), carbon sequestration by terrestrial ecosystems is the net removal of carbon dioxide (CO_2) from the atmosphere or the avoidance of atmospheric carbon dioxide (CO_2) emissions from terrestrial ecosystems. This removal process involves the absorption of CO2 from the atmosphere by all chlorophyll plants through photosynthesis. This carbon is stored as plant biomass (in the stems, branches, leaves, and roots of plants) and organic matter in the soil. Carbon sequestration in landscapes depends on land management practices and various ecosystem conditions that support established vegetation over longer periods of time. Defined carbon sequestration as the adoption of land management practices that increase net primary productivity, reduce heterotrophic respiration, or both, and result in increased ecosystem carbon storage. Planting trees, reducing tillage intensity, or restoring pastures on degraded lands will increase carbon stocks in plants, soils, or both.

II. Methods

Mountainous areas with a mosaic of ecosystem cover and the superposition of different eras of development, a combination of formal and informal practices, can create the impression of anarchy, which should be understood in order to identify patterns of order and dynamics [3,5]. The study region in the Eastern Caucasus covers the territory of the Chechen Republic. It includes both lowland semi-desert and steppe regions, as well as mountainous ones. The spectrum of altitudinal zones includes mountain-forest foothills and low mountains, transitioning with increasing altitude to mountain-steppe basins, mountain-meadow and nival-glacial. Currently, the most developed landscapes in the Chechen Republic are the foothill-steppe landscapes, where approximately 80% of the population lives. Large differences in altitude have created a variety of climatic conditions. With increasing altitude, the amount of precipitation increases (from 300 mm on the plain to 1400-1700 mm in the mountains). In intermountain basins, precipitation decreases to 600-700 mm. Given the interdisciplinary nature of the problem, the study incorporated both qualitative and quantitative methods. Qualitative methods focused on the analysis of historical documents, interviews with decision-makers, including local forest resource users, field observations, and route notes. Quantitative methods included mapping landscape diversity and forest dynamics, followed by geoinformation processing. The research was conducted using the following methods: route landscape surveys for studying mountain meadow landscapes, which allow for the collection of detailed information on vegetation cover, landscape structure, and the physical location of objects, providing a comprehensive understanding of the characteristics of each specific landscape area; the use of modern technology and satellite imagery; and expeditionary research aimed at obtaining high-quality data directly in the field, including surveys of vegetation, soils, and landscape characteristics using qualitative description methods.

III. Results

The concept of landscape structure for calculating carbon sequestration underlies the extrapolation of data obtained on carbon dynamics in a specific natural complex. Three main types of landscape structure are distinguished, corresponding to landscape responses to the impacts and changes in energy fields: vertical, horizontal (morphological), and temporal.

Vertical structure underlies the response of landscape components primarily to vertical flows of matter and energy (sun rays, air masses, precipitation, soil moisture, etc.). A connection between the type of vertical structure and the state of the natural complex has been proven [2, 12].

Horizontal (morphological) structure is formed through the horizontal redistribution of matter and energy flows. Elementary natural complexes (facies) are combined into more complex hierarchically subordinated spatial-morphological units, which underlies classical landscape science [7, 11, 15]. The temporal structure of landscapes is represented by a regular set and alternation of states during daily, seasonal, or multi-year changes in hydrothermal and other processes. By studying patterns in the dynamics of these states and identifying ethological cycles, the basis is laid for interpolating the obtained point-in-time data over longer periods (seasons, years).

Field data and analysis of all three types of landscape structures were used to identify the conditions of carbon dynamics in the Chechen Republic. Field expedition methods were used to study the morphological structure of landscapes, including the establishment of complex profiles in different altitudinal zones and belts, the interpretation of high-resolution satellite images, and the use of geoinformation methods to identify landscape habitats based on a digital elevation model and the creation of derivative layers (aspects, slope angles).

The soil organic carbon pool is the largest among terrestrial pools. The soil carbon pool is more than three times the size of the atmospheric pool (760 Gt) and approximately 4.5 times the size of the biotic pool (560 Gt). The soil carbon pool, or soil pool, is estimated at 2,500 Gt to a depth of 2 m. Of this, the soil organic carbon pool accounts for 1,550 Gt, and soil inorganic carbon and elemental pools account for the remaining 950 Gt. Restoring the soil organic carbon pool on cropland represents a potential sink for atmospheric CO_2. Changes in soil organic carbon (both short-term and long-term) are highly dependent on agricultural activities. A wide range of land use and soil management practices increase the density and distribution of soil organic carbon in the soil. These practices include mulching, conservation tillage, crop rotation with legumes, and the use of cover crops. In addition to plants, carbon dioxide can be captured as a pure byproduct of processes related to oil refining or from flue gases from electricity generation.

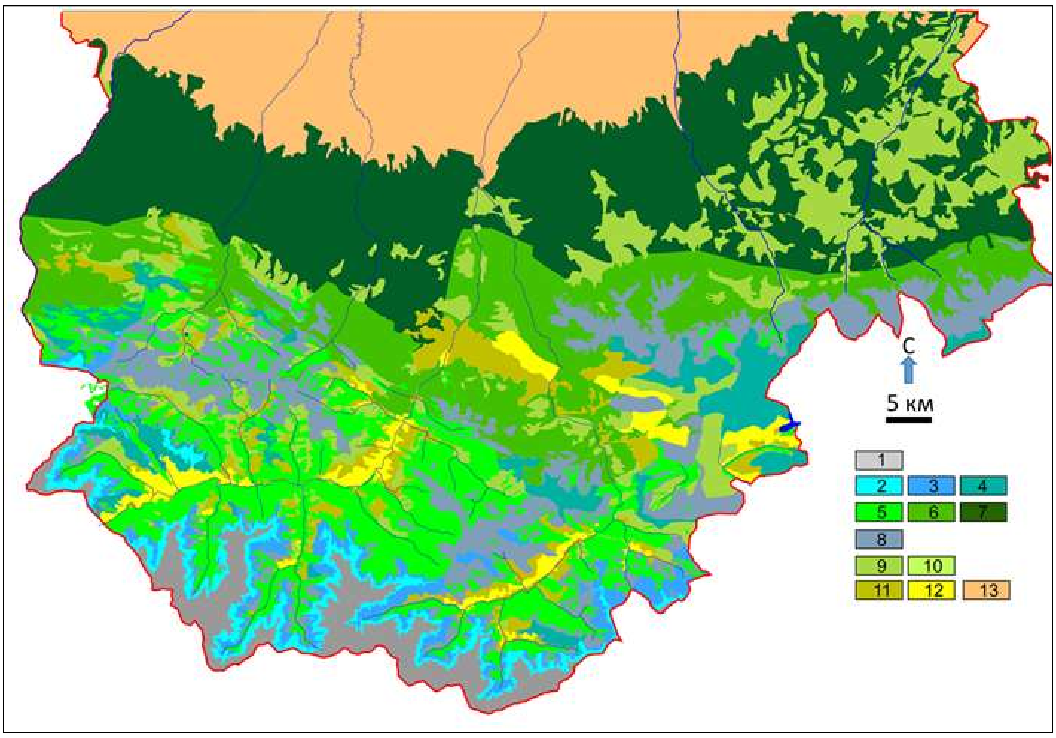
During photosynthesis, plants absorb carbon and return some of it to the atmosphere through respiration. The carbon that remains in plant tissue is then consumed by animals or added to the soil as litter when plants die and decompose. The primary way carbon is stored in the soil is as soil organic matter. Soil organic matter is a complex mixture of carbon compounds consisting of decomposing plant and animal tissue, microbes (protozoa, nematodes, fungi, and bacteria), and carbon bound to soil minerals. Carbon can be stored in the soil for millennia or quickly released back into the atmosphere. Climatic conditions, natural vegetation, soil composition, and drainage influence the amount and duration of carbon stored in the soil.

Along with studying CO_2 emissions from soils, soil catalase activity was determined using the gasometric method. Physicochemical soil parameters, such as humus content, were measured using the Tyurin method, and soil acidity was measured using the potentiometric method.

Natural forests are more resilient to climate change and disturbances than plantations due to their genetic, taxonomic, and functional biodiversity. This resilience includes post-fire recovery, resistance to and recovery from pests and diseases, and adaptation to changes in radiation, temperature, and water availability (including those resulting from global climate change). Although the genetic and taxonomic composition of forest ecosystems changes over time, natural forests will continue to absorb and accumulate carbon as long as there is sufficient water and solar radiation for photosynthesis. Green carbon in natural forests is stored in more reliable reserves than in industrial forests, especially over ecological timescales. Carbon stored in industrial forests is more susceptible to loss than that stored in natural forests. Industrial forests, especially plantations, have reduced genetic diversity and structural complexity, and consequently reduced resilience to pests, diseases, and changing climate conditions. Carbon stocks in forests subject to commercial harvesting, and particularly in monoculture plantations, will, on average, always be significantly lower (~40-60% depending on land use intensity and forest type) than those in natural, undisturbed forests.

Currently, research into the biosphere role of forests, their productivity, and sustainability in the face of global climate change has renewed interest in studying nitrogen cycling in forests. Accounting for nutrient cycling in individual units is still very rough. A systems approach and the construction of conceptual balance models are widely used as a methodological basis for studying nutrient cycling in biogeocenoses. This system of describing a community is used to objectively predict the future of the community, evaluate interventions within the community, and select those that will be beneficial for both the development of the community and its practical functioning [6, 8,12].

Landscapes that represent altitudinal zonation in the mountains of the Chechen Republic are presented by seven main types (altitude zones) and 13 subtypes (belts) (Figure 1). The altitudinal zones form the following landscape types, listed from the highest positions to the lowest: 1) nival-glacial; 2) mountain-meadow (represented by mountain-meadow subnival-alpine, mountain-meadow subalpine, mountain-meadow steppe); 3) mountain-forest (represented by mountain-forest small-leaved and coniferous-small-leaved, mountain-forest mixed broad-leaved and small-leaved, mountain-forest broad-leaved); 4) mountain-forest-meadow; 5) mountain-forest-meadow-steppe (represented by typical mountain-forest-meadow-steppe and mountain-forest-meadow-steppe and forest-steppe); 6) mountain-steppe (represented by mountain-steppe meadow and mountain-dry-steppe shrub); 7) foothill-steppe and forest-steppe.



Legend: nival-glacial – 1; mountain-meadow: 2 – subnival-alpine, 3 – subalpine, 4 – steppe; mountain-forest: 5 – small-leaved and coniferous-small-leaved, 6 – mixed broad-leaved and small-leaved, 7 – broad-leaved; mountain-forest-meadow – 8; mountain-forest-meadow-steppe: 9 – typical, 10 – A38 and forest-steppe; mountain-steppe: 11 – meadow: 12 – mountain-dry-steppe shrub; foothill-steppe and forest-steppe – 13.

Figure 1. Types and subtypes of mountain landscapes of the Chechen Republic

To describe ecosystems, components (plants, animals, soils, etc.) are identified and flows of matter, energy, or informational connections are established between them. Ecosystem connections with external entities—the atmosphere, groundwater, etc.—are also identified. Conceptual balance models represent a graphical or tabular representation of a set of components and the flows linking them with quantitative characteristics. The nitrogen cycle is the most complex of all chemical cycles.

Nitrogen is involved in all processes of organic synthesis and degradation, and also has its own microbiological cycle of entry from the atmosphere into the soil, transformation from organic to mineral forms, and release from the soil into the atmosphere. A detailed diagram of the nitrogen cycle, including the processes of microbiological transformation of its compounds, is highly complex, even at a qualitative level, and its individual components are subject to varying levels of study. The internal nitrogen cycle includes nitrogen uptake from its mineral compounds by vegetation, its conversion to mortmass upon the death of various living organisms, its processing along with soil humus by microorganisms, the mineralization of nitrogen-containing organic compounds to mineral forms, and humification. The external nitrogen cycle represents the combined processes of nitrogen input into the biogeocenosis from the atmosphere via precipitation and dust, nitrogen fixation, and nitrogen loss through leaching into underlying horizons from the root zone and through gaseous release.

The level of soil carbon sequestration is significantly affected by the established ratio of dry organic matter fractions in the total forage biomass. When converting the plant matter of grassland ecosystems to carbon, the conversion factors presented in Table 1 can be used. The data in Table 1 indicate that green phytomass has a higher carbon capacity than other plant matter fractions.

Table 1. Coefficients for converting dry plant matter of grassland ecosystems into carbon

№ п/п	Plant matter fractions	Coefficient
1.	Green phytomass	0,42
2.	Rags + litter	0,40
3.	Living roots	0,38
4.	Aboveground mortmass	0,35
5.	Subterranean mortmass	0,35

As grass stands age, carbon sequestration tends to increase, and the conversion rate may be higher. Equilibrium carbon dioxide levels in forage reservoirs (accumulation equals losses) are reached after 30-70 years of moderate natural resource management. However, meadow soils with low organic matter content can sequester more carbon over a longer period.

The nature of carbon sequestration in pastures is less predictable. In natural pastures, biomass is partially returned with livestock organic matter, resulting in sequestration, on average, not exceeding 4% of net primary production. It is only known for certain that the type of livestock grazed and the intensity of grazing are factors that significantly influence the level of biomass sequestration. Moderate grazing under rotational grazing does not impede the absorption of CO_2 from the atmosphere by pastures, since rotational grazing in different areas potentially stimulates biomass growth. Carbon sequestration rates in different types of forage ecosystems are significantly differentiated.

Intensive and unsystematic grazing, even on mature pastures, leads to the destruction of the stability and strength of the root system, preventing it from acting as active carbon sinks, which is often the dominant factor. Consequently, degradation of the root system, which accounts for 80-90% of the total phytomass, leads to the release of additional CO_2 from the primary carbon storage reservoir.

When harvesting hay, almost all aboveground biomass is removed without excretion, meaning no organic residue remains on the site. If mowing is particularly intensive and occurs intermittently, the amount of plant biomass (carbon) will inevitably decrease. Thus, the amount of accumulated CO_2 varies proportionally to the intensity of biomass removal from the site, depending on the species composition and density of the grass stand. Pastures that are annually overstocked are characterized by a steady accumulation of organic matter, accompanied by increased methane and nitrous oxide emissions from forage lands. Furthermore, intensive trampling of grassland significantly reduces the biodiversity of the grassland, which threatens to reduce biomass (carbon accumulation) and the forage value of pastures.

The carbon content of natural forages can be somewhat increased by switching to a rotational grazing system. However, this will lead to a certain increase in the labor intensity of pasture livestock farming and the cost of its production. Thus, with targeted management, natural grassland ecosystems can make a significant contribution to carbon dioxide accumulation.

The largest contribution to carbon sequestration, taking into account the area of forage land, comes from croplands abandoned in recent decades. The average CO_2 content in the organic matter of litter and plant associations of overgrown cropland is 46.1%. Within 4-5 years of being withdrawn from cultivation, soil profiles become more capacious reservoirs for the stable removal of CO_2 from the atmosphere. The rate of carbon dioxide accumulation depends primarily on the soil thickness, the length of time it takes for the arable land to become overgrown, and the type of fertile horizon.

The carbon regime of natural meadows can be somewhat adjusted through the use of mineral fertilizers, liming, and other agrochemical techniques. For example, the addition of nitrogen to the soil will increase the biological productivity of hayfields and pastures and enhance the rate of carbon dioxide sequestration. Subsequent bacterial nitrogen fixation will ensure the deepening of the carbon distribution profile in the lower organomineral fractions of the soil, expanding the carbon capacity of the soil reservoir. Furthermore, the active microbial composition of soil fractions significantly suppresses heterotrophic respiration. This method of additionally stimulating carbon accumulation is highly effective, as the soil CO_2 reservoir in virgin lands is relatively stable. The stability of carbon deposits on abandoned lands, in the absence of external influences, is measured in centuries. At the same time, it is important to keep in mind that an overdose of nitrogen at a certain stage will cause increased nitrous oxide emissions, which may outweigh the benefits of carbon dioxide absorption. The effect will be at least neutral or positive.

Biotic and abiotic variability in soil carbon sequestration capacity may change under climate change. Nutrient availability, the composition of soil fauna and microbial communities, and vegetation types depend on climate specificity and its seasonal variability, as well as the nature of the long-term hydrothermal trend. Therefore, the evolutionary adjustment of seasonal hydrothermal parameters across latitudinal and altitudinal natural zones will alter the established pattern of organic matter conversion into subsurface carbon by natural food sources.

A limiting factor for carbon dioxide sequestration may be increasingly frequent, abnormally dry periods, which will affect plant photosynthesis and lead to the evolutionary steppeization of grassland ecosystems, inevitably weakening their role in the decarbonization process.

An earlier spring and a slight shift in the autumn season may have the opposite effect on the carbon balance. If this trend continues, we can predict an extension of the grass growing season, and consequently, an increase in the biotic component of meadows in the carbon cycle. This applies primarily to northern latitudes, where more productive plants will thrive and temporal and spatial peaks will shift.

These assumptions will be valid with an adjustment for the previous cumulative effect of specific hayfields and pastures. This cumulative effect should serve as the starting point for the expected dynamics of carbon sequestration. Given the volatility of global warming, it is extremely difficult to accurately predict the net production of grassland ecosystems. Judging by the dynamics of carbon sequestration over the first two decades of the new century, the average annual sequestration rate is growing at 0.4% per year.

The accumulation of carbon dioxide in hayfields and pastures is characterized by a wider dispersion and depends on the botanical composition of the grassland and its use, the hydrothermal conditions of the area, and soil types. Moreover, the volume of soil carbon dioxide sequestration shows a noticeable downward trend over time, even with traditional land management remaining unchanged for many years.

Grazing natural meadows with moderate land management has a carbon advantage over harvesting hay. Relying on organic livestock feed for carbon sequestration is preferable to the use of agrochemicals.

IV. Conclusion

Observations at a carbon station in low-mountain broadleaf forest landscapes, including gas dynamics, as well as data from other researchers [4, 9], show that a significant portion of the phytomass is converted into mortmass, which, upon decomposition, returns to the atmosphere along with volatile gases. In these phytocenoses, which have reached climax states, carbon emission predominates over runoff.

The mortmass of mountain meadow landscapes consists of slowly decomposing rags and litter. In turf-grass communities, rags can exceed green phytomass and reach 2 t/ha. The underground phytomass of roots is significant, accounting for more than half of the total phytomass. Factors contributing to carbon accumulation in these landscapes include intense solar energy and a relatively short growing season. The prevalence of primitive soils also contributes to low carbon emissions [10, 11, 14]. Aboveground phytomass reserves in subalpine meadows reach 2-3.5 t/ha, with typically higher mortmass values. Under mixed-grass meadows (reed grass, fescue, etc.), particularly in flattened areas, deep and medium-deep soils form, where carbon is deposited. These meadows also have high reserves of belowground phytomass.

On the northern slopes, meadows with rhododendron (*Rhododendron caucasicum Pall.)* thickets are found, where aboveground phytomass increases to 6-10 t/ha, with low herbaceous phytomass values (0.7 t/ha). Soddy-peaty soils, also with active carbon accumulation, develop beneath these meadows.

Observations show that, upon reaching the climax and quasi-climax stages, broadleaf forests, instead of sequestering carbon, begin to actively release it through respiration [1,13,15]. Mortmass mineralization is accompanied by the emission of volatile gases; only a small amount of carbon enters the soil. Furthermore, under the canopy of mature broadleaf forests, the grass cover is sparse, leading to the destruction of the upper soil horizons and their erosion into the lower parts of the slopes. In mountain-steppe landscapes, carbon accumulates primarily in the underground part of the plant community, in the mortmass (primarily underground) and soil humus. Observations show that the ground layers of the mortmass, which transition into the upper soil layers, are critical for understanding carbon dynamics. Carbon accumulation in the main carbon-containing components of mountain landscapes—soils and vegetation—is hampered by climate instability, slope processes, and economic activity.

The opposite is observed in high-altitude landscapes, where phytomass transforms into waste and litter, replenishing the upper soil horizons. The prevalence of subzero temperatures reduces soil respiration and carbon loss. In the mid-altitude zone, due to a lack of moisture, herbaceous phytomass is relatively small, and a certain portion is consumed by livestock. The resulting mortmass enters the soil and is partially returned to the atmosphere through biogenic degradation.

Acknowledgments: This study was carried out within the framework of the State assignment: "Ecological diagnostics of carbon sequestration in the landscapes of the Chechen Republic" (FEGS-2021-0010).

CONFLICT OF INTEREST.

Authors declare that they do not have any conflict of interest.

References

[1] Abalori T.A., Cao W., Weobong C.A.-A., Wang S., Anning D.K., Sam F.E., Liu W., Wang W. Spatial variability of soil organic carbon fractions and aggregate stability along an elevation gradient in the alpine meadow grasslands of the Qilian Mountains, China // Chilean Journal of Agricultural Research, 82(1). 2022. 52–64. https://doi.org/10.4067/s0718-58392022000100052).

[2] Alferov AM, Blinov VG, Gitarsky ML et al. Monitoring greenhouse gas flows in natural ecosystems // Saratov: Amirit. 2017. – 279 p.

[3] Beruchashvili N.L., Zhuchkova V.K. Methods of complex physical-geographical studies // Moscow: Moscow State University Press, 1997. 320 p.

[4] Bakaeva Z.M., Zamolodchikov D.G. Carbon reserves and fluxes in the forests of the North Caucasus // News of universities. North Caucasian region. Series: Natural sciences. - 2009. - No. 5. - pp. 78–82.

[5] Gakaev R. Natural and man-made climate changes in the Holocene / R. Gakaev, A. Daukaev // Reliability: Theory & Applications. – 2024. – Vol. 19, No. S6(81). – P. 637-641. – DOI 10.24412/1932-2321-2024-681-637-641.

[6] Gunya A. Cartographic display of landslide areas and landscape-geomorphological profiling of landslide slopes in the territory of the Chechen Republic / A. Gunya, R. Gakaev // Reliability: Theory & Applications. – 2024. – Vol. 19, No. S6(81). – P. 560-566. – DOI 10.24412/1932-2321-2024-681-560-566.

[7] Gakaev R. Manifestations of natural and man-made geodynamic processes and risks on the territory of the Chechen Republic / R. Gakaev, A. Daukaev, L. Gatsaeva // Reliability: Theory & Applications. – 2024. – Vol. 19, No. S6(81). – P. 924-929. – DOI 10.24412/1932-2321-2024-681-924-929. – EDN UTMTNN.

[8] Kalov R.O. Place of natural grass ecosystems in the global carbon balance / R.O. Kalov, R.A. Gakayev // Problems of regional ecology. - 2022. - No. 6. - pp. 50-54. - DOI 10.24412/1728-323X-2022-6-50-54.

[9] Kurganova I.N., Karelin D.V., Kotlyakov V.M. et al. Pilot national network for monitoring soil respiration in Russia: first results and development prospects / I.N. Kurganova, D.V. Karelin, V.M. Kotlyakov et al. // Reports of the Russian Academy of Sciences. Earth Sciences. - 2024. - Vol. 519, No. 1. - pp. 550–559. DOI: 10.31857/S2686739724110197.

[10] Lukina N. V., Bartalev S. A., Geraskina A. P., Plotnikova, Gornov A. V., Ershov D. V., Gavrilyuk E. A., Kuznetsova A. I., Shevchenko N. E., Tikhonova E. V., Danilova M. A., Tebenkova D. N., Smirnov V. E., Ruchinskaya E. V. The role of old-growth forests in the accumulation and storage of carbon // Bulletin of the Russian Academy of Sciences. Geographical Series, 2023, Vol. 87, No. 4. pp. 536-557. DOI: 10.31857/S2587556623040064.

[11] Petrushina M.N. Aboveground Herbaceous Phytomass and Mineral Reserves in It in the Landscapes of the Argun Historical, Architectural and Natural Museum-Reserve / M.N. Petrushina // North Caucasian Complex Expedition: Works / Responsible. Editors A.N. Gunya, M.N. Petrushina. Issue. 2. // Grozny: ChSU, Makhachkala: ALEF, 2021. - pp. 95-113.

[12] Petrushina M.N. Features of the functioning of the Makazhoy basin landscapes in the winter and summer periods of 2022 // Comprehensive study of mountain ecosystems. - Grozny: FSBEI HE "Chechen State University named after A.A. Kadyrov" 2023. - pp. 267-274.

[13] Physical and geographical differentiation of the territory of the Chechen Republic / A. N. Gunya, M. N. Petrushina, A. V. Lysenko [et al.] // Contemporary issues of geography and geology: Dedicated to the 100th Anniversary of the Yerevan State University, International Conference Proceedings, Yerevan, September 27–29, 2018 / Yerevan State University, Faculty of Geography and Geology. – Yerevan: Yerevan State University Publishing House, 2018. – P. 69–74.

[14] Samoilova G.S., Avessalomova I.A. Mountain regions of Russia: morphometric analysis and landscape diversity // Study of the mountains. Mountain regions of northern Eurasia. Development in the context of global changes / Questions of geography. Coll. 137. Ed. V.M. Kotlyakov, Yu.P. Badenkov, K.V. Chistyakov. - Moscow: ID Kodeks. 2014. - pp. 39-63.

[15] Wohl E., Dwire K., Sutfin N., Polvi L., Bazan R. 2012. Mechanisms of carbon storage in mountainous headwater rivers // Nature Communications 3:1263. https://doi.org/10.1038/ncomms2274.