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Article

Variability of organic carbon stocks in soils and vegetation of the Highland (Inner Mountainous) Dagestan

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Abstract. This study evaluates the relationship between soil-climatic differences and the accumulation of soil organic carbon (C_{org}) stocks in the soil cover of an orographically enclosed intermountain zone on slopes of contrasting exposure within the Dutsnabek and Chakulabek mountain ranges (Eastern Caucasus). The research was conducted at the “Tsudakhar” experimental site of the Mountain Botanical Garden, Dagestan Scientific Center, Russian Academy of Sciences (1100–1250 m a.s.l.), under a protected (reserve) regime. C_{org} accumulation was analyzed on the arid southern slope (mountain meadow-steppe soil) and the humid northern slope (mountain meadow-forest soil). Vegetation cover on the southern slope (Dutsnabek) was 10% lower, and species richness was 36 units lower compared to the northern slope (Chakulabek). C_{org} content in the top 40 cm soil layer ranged from 1.42% to 2.11%, with organic carbon stocks on the southern slope being 45.23% lower than on the northern slope. Additionally, the southern slope exhibited significantly lower biomass accumulation: 48.40% less in green biomass and 65.28% less in root biomass. Significant correlations (according to Chedoke scale) were found between C_{org} stocks and vegetation productivity indicators as well as soil physical properties: positive correlations with soil moisture and negative correlations with bulk density and temperature.

Keywords: mountain ecosystems, phytocenosis, floristic composition, species richness, climate aridization, soil-climatic factors, humus, correlation

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Научная статья

Вариабельность запасов органического углерода в почвах и растительности Внутригорного Дагестана

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Аннотация. Дана оценка взаимосвязи между почвенно-климатическими различиями и накоплением запасов почвенного органического углерода (C_{org}) в почвенном покрове орографически замкнутой межгорной зоны на склонах разной экспозиции хребтов Дуцнабек и Чакулабек (Восточный Кавказ). Исследование проведено в районе Внутригорного Дагестана (1100–1250 м н.у.м.) на участках экспериментальной базы «Цудахарская» ГорБС ДФИЦ РАН в

условиях заповедного режима. Работа по выявлению накопления $C_{\text{орг}}$ в почвах проводилась на южном аридном (горная лугово-степная почва) и северном гумидном (горная лугово-лесная почва) склонах территории. Проективное покрытие южного склона (Дуцнабек) по сравнению с северным (Чакулабек) было ниже на 10%, видовая насыщенность – ниже на 36 единиц. Содержание $C_{\text{орг}}$ в почвенном слое толщиной 40 см колебалось в пределах 1.42–2.11%, при этом на южном склоне запас органического углерода был на 45.23% ниже, чем на северном. Также на южном склоне наблюдалось меньшее накопление фитомассы: на 48.40% в зеленой массе и 65.28% в корневой. Были обнаружены значимые коррелятивные связи по шкале Чеддока между запасами углерода и показателями продуктивности фитоценоза с физическими свойствами почвы: прямая связь с влажностью и обратная – с плотностью и температурой.

Ключевые слова: горные экосистемы, фитоценоз, флористический состав, видовая насыщенность, аридизация климата, почвенно-климатические факторы, гумус, корреляция

Финансирование. Исследование выполнено в рамках государственного проекта «Динамика почвенного покрова и биопродуктивности экосистем Северо-Западного Прикаспия и Восточного Кавказа» (проект № АААА-А20-120062990014-2).

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Introduction

Agricultural management entails a range of environmental challenges, including the depletion of soil organic carbon ($C_{\text{орг}}$) stocks and increased emissions of greenhouse gases (Bossio et al., 2020). Controlling $C_{\text{орг}}$ preservation is critical for ecosystem processes – particularly the carbon cycle in terrestrial ecosystems – since carbon directly influences atmospheric composition and the rate of climate change. It is well established that minor changes in soil carbon content can significantly affect atmospheric CO_2 concentrations, leading to adverse consequences for terrestrial ecosystems (Bradford et al., 2016). Moreover, maintaining $C_{\text{орг}}$ plays a pivotal role in enhancing soil fertility and regulating agricultural productivity (Gerke, 2022).

Climate change, along with associated agricultural practices (crop selection, organic fertilization, irrigation, agroforestry, crop rotation), alters the physicochemical and biological properties of soils under intensive land use (Jia et al., 2022; Skadell et al., 2023). Thus, understanding the distribution of $C_{\text{орг}}$, mechanisms controlling its dynamics, and the influence of various factors on its preservation enables proactive environmental management. Climate warming contributes to the loss of $C_{\text{орг}}$ stocks (Dong et al., 2021), while soil changes directly affect the rates of carbon accumulation and loss (Lal, 2004).

Accurate assessment of C_{org} accumulation is essential for quantifying carbon sequestration by terrestrial ecosystems and for monitoring changes in accumulation rates driven by anthropogenic activities (agriculture, urbanization, industrialization, mining, etc.) or climatic shifts. Increasing C_{org} stocks in terrestrial ecosystems represents one of the most effective and cost-efficient strategies for mitigating the rise of atmospheric CO_2 concentrations (Anjum et al., 2022).

Russia accounts for approximately 10% of the Earth's land surface and holds nearly one-fifth of the world's total soil carbon stocks. Soil mapping relies primarily on data from soil profiles characterizing organic carbon content (De Anta et al., 2020; Mirchooli et al., 2020). Consequently, reliable estimation of C_{org} stocks and their spatial distribution across Russia remains an urgent scientific priority.

C_{org} stocks in Russia's natural ecosystems have been estimated by several researchers using either typical soil profile parameters (Abakumov et al., 2022; Chernova et al., 2021) or averaged C_{org} values from national databases (Chestnykh et al., 2022; Husniev et al., 2020). In these studies, C_{org} distribution has been analyzed using various regionalization schemes: ecological (Adhikari et al., 2020; Zhou et al., 2021), administrative (Chernova et al., 2021), and forest-based (De Anta et al., 2020).

It is important to note that carbon accumulation in natural systems is strongly influenced by grassland productivity and soil-climatic conditions. Therefore, data on C_{org} accumulation, its natural dynamics, and trends in undisturbed, protected ecosystems of specific regions provide a foundational basis for forecasting transformations induced by climate change and the conversion of natural ecosystems to agricultural use.

The objective of this study is to analyze the relationship between soil-climatic differences and C_{org} accumulation in the soil-vegetation cover of south- and north-facing slopes within the intermountain zone of the Republic of Dagestan (Eastern Caucasus, southern Russia). The data presented here can be used to improve or validate C_{org} prediction models, such as geostatistical models (Yigini and Panagos, 2016).

Materials and methods

The study of soil organic carbon (C_{org}) content and stocks was conducted in the intramountain (intermountain) region of Dagestan at an elevation of 1100–1250 m a.s.l. Two permanent experimental plots (PEPs), each measuring 100 m², were established at the “Tsudakhar” Experimental Station of the Mountain Botanical Garden (MBG DSC RAS), under a protected (reserve) regime. The GPS coordinates of the plots were as follows: northern slope of the Chakulabek ridge – N 42.327640 E 47.166180; southern slope of the Dutsnabek ridge – N 42.328297 E 47.164353 (Fig. 1).

Field experiments were carried out during the summer months from 2012 to 2021. Over this 10-year period, the average productivity indicators of phytocenoses and soil-climatic characteristics were recorded on both plots. Vegetation descriptions were conducted annually in August – the period of maximum seasonal floristic diversity – from 2012 to 2021. The floristic composition of both plots was fully documented in August 2021.

Soil names follow the classification system of the USSR (Egorov et al., 1977), adapted to regional characteristics (Diagnostika..., 1982; Zalibekov, 2010).

The soil cover of intramountain Dagestan is generally characterized by shallow, stony soil profiles, high rock fragment content, and significant susceptibility to water-induced slope erosion. Soil textures are predominantly medium-clayey. Soil humus content varies between 1.5% and 12%, depending on soil type and degree of water erosion. Soil reaction (pH) ranges from neutral (mountain meadow-steppe soils) to slightly acidic or acidic (mountain meadow-forest soils).

The soil on the northern slope is a shallow, eroded, heavy clayey, carbonate-bearing mountain meadow-forest soil developed on colluvial carbonate deposits. Soils of this type are poorly studied in Dagestan due to their limited and discontinuous distribution, covering only 27.8 thousand hectares (0.6%) of the republic's total area. These soils exhibit a dark-colored A horizon, with a gradual decrease in color intensity with depth.

The soil on the southern slope is a strongly eroded, heavy clayey, carbonate-bearing mountain meadow-steppe soil developed on dense colluvial limestone deposits. Such soils occupy 127.4 thousand hectares in Dagestan's land fund. Mountain meadow-steppe soils are typically found on landforms with insufficient moisture and evaporation rates exceeding total precipitation. The dominant textural class is heavy clayey, often silty-clayey. In addition to high skeletal content, the morphological structure of these soils is characterized by a shallow combined A+B horizon thickness of only 30–40 cm.

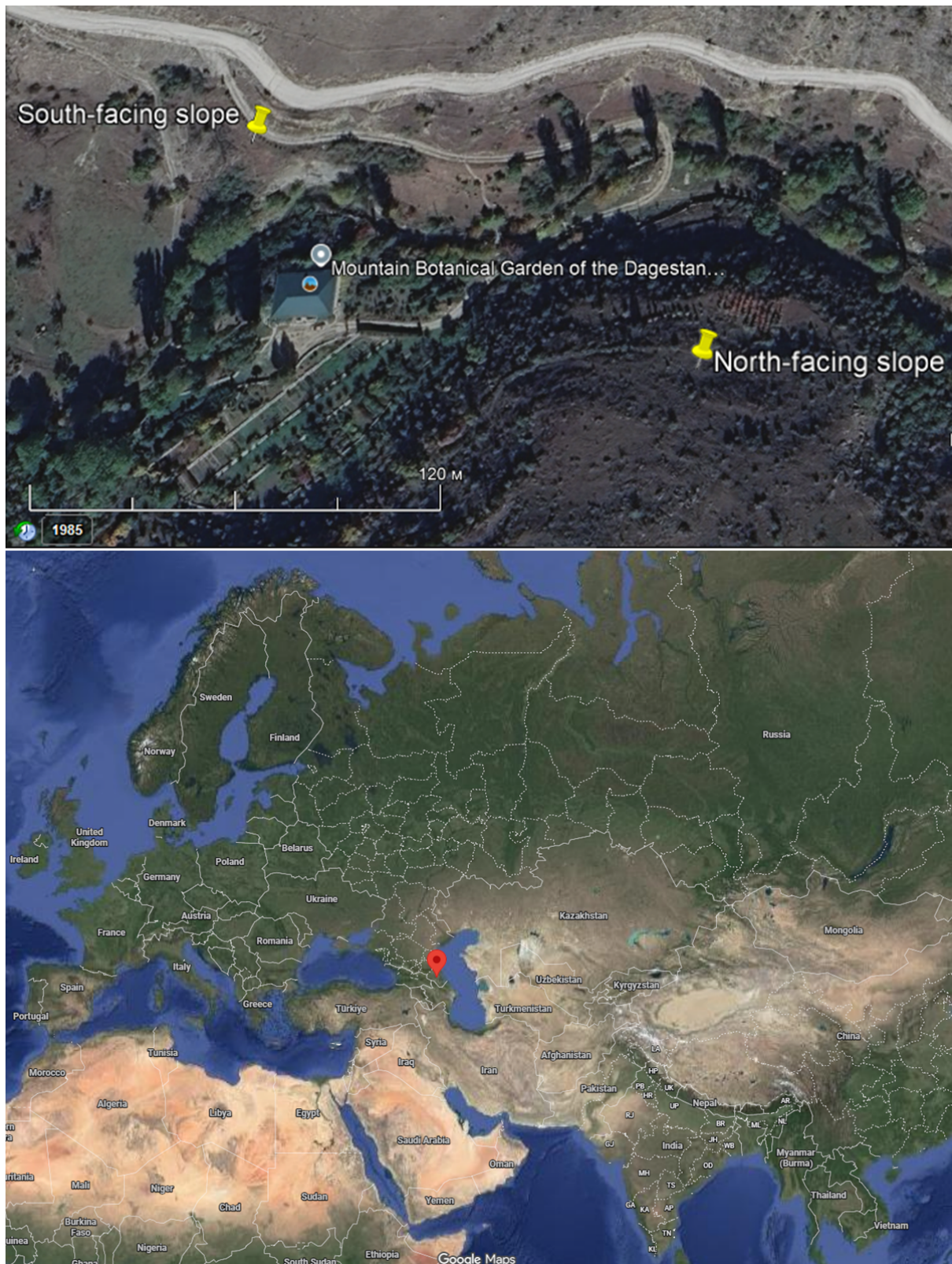


Fig. 1. Map of the location of the studied sites of the Tsudakhar Station.

To determine C_{org} stocks, soil samples were collected from root-active layers at 0–20 cm and 20–40 cm depths, following GOST 17.4.4.02-2017¹. These depths were selected because the 0–40 cm soil layer is primarily responsible for rapid responses to environmental changes in the C_{org} cycle (Wan et al., 2019; Zhong et al., 2021). The accuracy of C_{org} content estimation is highly dependent on the precise determination of soil bulk density (Xu et al., 2019). In this study, soil bulk density was measured according to RD 52.33.219², based on the volume determined directly from soil core sampling.

Assuming that all input parameters (M , R , and H) in the working equation for density determination are independent, the variance of the density (ρ) is equal to

$$u^2(d) = \left(\frac{\partial d}{\partial M} \right)_{R,H} u^2(M) + \left(\frac{\partial d}{\partial R} \right)_{M,H} u^2(R) + \left(\frac{\partial d}{\partial H} \right)_{M,R} u^2(H),$$

where $u(H)$ and $u(M)$ – standard uncertainty of the independent measured parameters (M , R и H);

$\left(\frac{\partial d}{\partial M} \right)_{R,H}$, $\left(\frac{\partial d}{\partial R} \right)_{M,H}$ and $\left(\frac{\partial d}{\partial H} \right)_{M,R}$ are the sensitivity coefficient for density, which can be readily calculated from the working equation $d = M / (\pi R^2 H)$ by differentiating.

The combined standard uncertainty is the square root of the variance $u^2(d)$ ³. The relative combined expanded uncertainty of the density (d) measurement at a 95% confidence level can be calculated using the following simple equation (where $k = 2$ is the coverage factor). Thus, the combined expanded relative uncertainty of soil density measurements (at a 95% confidence level with a coverage factor ($k = 2$)) was estimated as $U_r(d) = k u_r(d) = 1.0\%$.

Carbon in the samples was determined using the Tyurin method (FAO, 2021) by oxidizing organic matter with a mixture of $H_2SO_4 + K_2C_2O_7$, followed by measurement using a KFK-2MP photoelectric concentration colorimeter (Russia, CJSC “Zagorsky Optical-Mechanical Plant,” Sergiev Posad, Russia). Aboveground biomass was assessed using the clipping method, while root biomass was sampled simultaneously from the same plots after clipping the aboveground vegetation, to a depth of 40 cm, using the monolith method (Bazilevich et al., 1978).

At all experimental sites, bulk soil density was measured at depths of 0–20 cm and 20–40 cm, with three replicates per depth. Based on the profile data for organic carbon (C_{org}) and bulk density, individual C_{org} stocks for each soil layer and the total organic carbon stock in the 0–40 m soil depth was calculated.

The total expanded relative uncertainty (confidence level 0.95, coverage factor $k = 2$) for C_{org} concentration determination was estimated at 1%.

Soil organic carbon stocks were calculated as follows (Yigini and Panagos, 2016):

$$Q = (m \times h \times d) \times 1000,$$

where Q is the C_{org} stock (kg/ha); m is the C_{org} content (%); h is the sampling depth (cm); and d is the bulk density of the soil layer (g/cm^3). The combined expanded relative uncertainty (confidence level 0.95, $k = 2$) for C_{org} stock determination was estimated at 2%.

Carbon content in phytomass was determined by titration with 0.2 N Mohr’s salt solution (Tret’yakov et al., 1990).

Carbon stocks in phytomass (C_{stock}) were calculated using the formula:

$$C_{stock} = P \times C\%,$$

where P is phytomass productivity (kg/ha) and $C\%$ is the carbon content in phytomass (%).

¹ GOST 17.4.4.02-2017. Soils. Methods of sampling and preparation of samples for chemical, bacteriological, and helminthological analysis.

² RD 52.33.219–2022 “Guidelines for determining agrohydrological properties of soil”.

³ Evaluation of measurement data – Guide to the expression of uncertainty in measurement. Web page. URL: https://www.bipm.org/documents/20126/2071204/JCGM_100_2008_E.pdf/cb0ef43f-baa5-11cf-3f85-4dcd86f77bd6 (accessed: 24.11.2025).

All analyses were performed in triplicate. Results are presented as mean values \pm standard deviations. Statistical analyses were conducted using the Statistica 6.0 software package (StatSoft Inc., USA). The critical level of statistical significance was set at $p \leq 0.05$. Normality of data distribution was assessed using the Shapiro–Wilk test ($p > 0.05$). Relationships between soil physical properties and soil carbon stocks as well as phytocenosis productivity were evaluated using Pearson's correlation coefficient. The strength and direction of linear associations between quantitative variables (soil physical properties, soil carbon stocks, and phytocenosis productivity) were determined using Pearson's correlation coefficient. Qualitative interpretation of correlation values followed the Chedoke scale (Kremmer, 2009), which classifies the strength of association as follows: weak (0.10–0.29), moderate (0.30–0.49), noticeable (0.50–0.69), high (0.70–0.89), and very high (0.90–1.00).

Results and discussion

The PEPs located on the north- and south-facing slopes of the Chakulabek and Dutsnabek ridges differed in their geomorphological, climatic, and floristic characteristics (Table 1).

Compared to the northern slope, the average solar irradiance on the southern slope between 14:00 and 15:00 over the 10-year period was 7714 lux higher, resulting in significantly greater heating: soil temperature on the southern slope was 8 °C higher. The slope gradient on the southern side is also twice as steep, leading to pronounced erosion. Vegetation cover on the northern slope is denser than on the southern slope, primarily because moisture persists longer after snowmelt due to poor soil warming during the spring-summer period.

Vegetation height on the northern slope is lower than on the southern slope. Different slope aspects lead to the development of distinct vegetation types (Zapata-Rios et al., 2016), differing in species diversity (Yang et al., 2020). The floristic composition of the studied phytocenoses included 97 species, of which 74 occurred on the northern slope and 38 on the southern slope (Table 2).

The vegetation on the northern slope of the Chakulabek ridge is predominantly shrub-friganoid, while on the southern slope of the Dutsnabek ridge it is semi-desert-steppe (Mallaliyev and Asadullaev, 2014).

Woody and shrub vegetation is very weakly developed on the southern slope. Trees are entirely absent; shrubs are represented only by *Ephedra procera* and *Onobrychis cornuta*. On the northern slope, tree species include *Armeniaca vulgaris*, *Pinus kochiana*, and *Malus orientalis*. Shrub vegetation comprises nine species, with *Rosa spinosissima* as the dominant. Of the 13 woody-shrub species present on the two slopes of contrasting exposure, only *Onobrychis cornuta* occurs on both, indicating a very low Jaccard similarity index (7.7%).

Table 1. Characteristics of the Tsudakhar Station plots (2012–2021), n = 10.

Polygon-transect parameters		Slope aspect	
		North-facing slope	South-facing slope
Elevation above sea level, m		1160	1130
Illuminance, lux		80824 \pm 2332	88538 \pm 2510
Slope gradient, °		17	33
on the surface		25.4 \pm 1.29	33.5 \pm 1.31
Soil's temperature, °C	0–20 cm	24.1 \pm 2.51	28.4 \pm 2.11
	20–40 cm	21.2 \pm 2.21	24.8 \pm 1.84
Sward height, cm		25 \pm 1.33	35 \pm 1.51
Herb layer projective cover, %		95	85

Table 2. Floristic composition of north- and south-facing plots at the Tsudakhar Station (Intramountain Dagestan) in 2021; "+" – single occurrence, "–" – species not detected.

No.	Species	Projective cover, %	
		North-facing slope	South-facing slope
	Tree layer overall	3	0
1	<i>Armeniaca vulgaris</i> Lam.	1	–
2	<i>Malus orientalis</i> Uglitzk.	1.5	–
3	<i>Pinus kochiana</i> Klotzsch	0.5	–
	Shrub layer overall	15	2
4	<i>Berberis vulgaris</i> L.	1	–
5	<i>Cotoneaster integerrimus</i> Medik.	0.5	–
6	<i>Ephedra procera</i> Fisch. & C.A. Mey.	–	+
7	<i>Juniperus oblonga</i> M. Bieb.	1	–
8	<i>Onobrychis cornuta</i> (L.) Desv.	1	2
9	<i>Rhamnus cathartica</i> L.	1.5	–
10	<i>Rhamnus tortuosa</i> Sommier & Levier	0.7	–
11	<i>Rosa canina</i> L.	1.5	–
12	<i>Rosa spinosissima</i> L.	6.3	–
13	<i>Spiraea hypericifolia</i> L.	1.5	–
	Herbaceous layer overall	95	85
14	<i>Achillea millefolium</i> L.	1.1	–
15	<i>Achnatherum caragana</i> (Trin.) Nevski	–	16
16	<i>Achnatherum virescens</i> (Trin.) Banfi, Galasso & Bartolucci	0.6	–
17	<i>Alchemilla sericata</i> Rchb. ex Buser	0.8	–
18	<i>Allium gunibicum</i> Misch. ex Grossh.	–	0.4
19	<i>Androsace villosa</i> L.	0.4	–
20	<i>Anthemis fruticulosa</i> M. Bieb.	1	–
21	<i>Artemisia armeniaca</i> Lam.	–	2.2
22	<i>Artemisia salsoloides</i> Willd	–	+
23	<i>Aster amelloides</i> Besser	0.5	–
24	<i>Bothriochloa ischaemum</i> (L.) Keng	8	29.5
25	<i>Bromopsis biebersteinii</i> (Roem. & Schult.) Holub	1.6	–
26	<i>Bupleurum polyphyllum</i> Ledeb.	0.2	–
27	<i>Campanula hohenackeri</i> Fisch. & C.A. Mey.	0.2	+
28	<i>Carex humilis</i> Leyss.	3.5	–
29	<i>Carlina vulgaris</i> L.	0.4	–
30	<i>Cichorium intybus</i> L.	–	0.2

No.	Species	Projective cover, %	
		North-facing slope	South-facing slope
31	<i>Cirsium argillosum</i> Petrov ex Kharadze	–	0.3
32	<i>Dianthus caucaseus</i> Sm.	0.3	–
33	<i>Diplotaxis muralis</i> (L.) DC.	–	0.4
34	<i>Echium russicum</i> J.F. Gmel.	+	–
35	<i>Echium vulgare</i> L.	–	+
36	<i>Elytrigia gracillima</i> (Nevski) Nevski	4.3	2.2
37	<i>Erigeron acris</i> L.	+	–
38	<i>Erysimum meyerianum</i> (Rupr.) N. Busch	–	0.5
39	<i>Euphorbia virgata</i> Waldst. & Kit.	0.5	1.4
40	<i>Euphrasia pectinata</i> Ten.	0.8	–
41	<i>Festuca woronowii</i> Hack.	5.5	–
42	<i>Filipendula vulgaris</i> Moench	2.8	–
43	<i>Fragaria viridis</i> Weston	4.9	–
44	<i>Galium humifusum</i> M. Bieb.	–	1.2
45	<i>Galium valantioides</i> M. Bieb.	0.2	–
46	<i>Gypsophila acutifolia</i> Fisch. ex Spreng.	–	5.5
47	<i>Gypsophila tenuifolia</i> M. Bieb.	0.6	–
48	<i>Helianthemum dagestanicum</i> Rupr.	0.8	–
49	<i>Helianthemum nummularium</i> (L.) Mill.	1.7	–
50	<i>Hypericum perforatum</i> L.	2.2	–
51	<i>Inula britannica</i> L.	–	0.6
52	<i>Inula germanica</i> L.	0.4	–
53	<i>Inula hirta</i> L.	5.8	–
54	<i>Jurinea ruprechtii</i> Boiss.	–	3.2
55	<i>Koeleria macrantha</i> (Ledeb.) Schult.	2.8	–
56	<i>Lactuca serriola</i> L.	–	0.6
57	<i>Leontodon hispidus</i> L.	0.7	–
58	<i>Linum austriacum</i> L.	+	–
59	<i>Linum tauricum</i> Willd.	–	0.8
60	<i>Medicago falcata</i> L.	2.6	0.9
61	<i>Melampyrum arvense</i> L.	0.9	–
62	<i>Melica transsilvanica</i> Schur	–	1.7
63	<i>Minuartia oreina</i> (Mattf.) Schischk.	0.2	–
64	<i>Onobrychis bobrovii</i> Grossh.	–	7.3
65	<i>Peucedanum ruthenicum</i> M. Bieb.	0.3	–
66	<i>Phlomis tuberosa</i> (L.) Moench	0.6	–

No.	Species	Projective cover, %	
		North-facing slope	South-facing slope
67	<i>Pilosella officinarum</i> F.W. Schultz & Sch. Bip.	0.7	–
68	<i>Pimpinella saxifraga</i> L.	0.4	–
69	<i>Plantago lanceolata</i> L.	1	0.5
70	<i>Plantago major</i> L.	–	+
71	<i>Plantago media</i> L.	0.5	–
72	<i>Poa pratensis</i> L.	2.7	–
73	<i>Potentilla bifurca</i> L.	–	1.8
74	<i>Potentilla crantzii</i> (Crantz) Beck ex Fritsch	0.8	0.3
75	<i>Potentilla recta</i> L.	+	–
76	<i>Psephellus daghestanicus</i> Sosn.	2	–
77	<i>Pseudomuscari pallens</i> (M. Bieb.) Garbari	0.3	–
78	<i>Pulsatilla albana</i> (Steven) Bercht. & J. Presl	0.5	–
79	<i>Reseda lutea</i> L.	–	1.2
80	<i>Salvia canescens</i> C.A. Mey.	7.2	1.9
81	<i>Salvia verticillata</i> L.	2.6	–
82	<i>Satureja subdentata</i> Boiss.	2.1	–
83	<i>Scabiosa gumbetica</i> Boiss.	2.2	–
84	<i>Securigera varia</i> (L.) Lassen	2.8	–
85	<i>Silene longipetala</i> Vent.	0.8	–
86	<i>Sonchus oleraceus</i> L.	–	+
87	<i>Stipa caucasica</i> Schmalh.	3.3	–
88	<i>Stipa daghestanica</i> Grossh.	2.2	–
89	<i>Stipa pennata</i> L.	–	3.1
90	<i>Taraxacum officinale</i> F.H. Wigg.	0.3	+
91	<i>Teucrium chamaedrys</i> L.	0.9	–
92	<i>Teucrium polium</i> L.	1.8	1.1
93	<i>Thalictrum foetidum</i> L.	0.9	–
94	<i>Thymus collinus</i> M. Bieb.	0.8	–
95	<i>Vincetoxicum funebre</i> Boiss. & Kotschy	0.4	–
96	<i>Vincetoxicum scandens</i> Sommier & Levier	0.3	–
97	<i>Ziziphora acinos</i> (L.) Melnikov	0.2	–

Table 3. Content of organic carbon in soils at the Tsudakhar Station (Intramountain Dagestan) during 2012–2021, n = 10.

Soil type, slope aspect, elevation above sea level	Depth, cm	Density, g/cm ³	Soil moisture, %	C _{org} , %	Carbon stocks, t/ha
Mountain meadow-forest soil, north-facing slope, 1160 m a.s.l.	0–20	1.07 ± 0.04	19.11 ± 1.14	2.58 ± 0.18	55.23 ± 2.09
	20–40	1.15 ± 0.04	17.68 ± 1.06	1.63 ± 0.11	37.44 ± 1.39
Mountain meadow-steppe soil, south-facing slope, 1130 m a.s.l.	0–20	1.08 ± 0.03	13.24 ± 1.19	1.69 ± 0.05	36.58 ± 1.30
	20–40	1.18 ± 0.03	16.89 ± 1.52	1.15 ± 0.03	27.23 ± 0.91

Herbaceous vegetation is characterized by a clearly dominant species on both slopes: *Bothriochloa ischaemum* (8% cover on the northern slope, 29.5% on the southern), a hemikryptophyte of widespread Mediterranean-Siberian origin and a typical species of the flora of intramountain Dagestan. On the southern slope, additional dominant species include *Achnatherum caragana* (16%) and *Onobrychis bobrovii* (7.3%). Other common species are *Gypsophila acutifolia*, *Salvia canescens*, *Stipa pennata*, *Jurinea ruprechtii*, *Elytrigia gracillima*, and *Potentilla bifurca*, among others. In contrast, the northern slope lacks a single dominant species and instead exhibits a group of co-dominants (*Bothriochloa ischaemum*, *Salvia canescens*, *Festuca woronowii*, *Inula hirta*, *Carex humilis*, and *Fragaria viridis*), each with a projected cover of 3.5–8%. Of the 84 herbaceous species recorded, only 10 are shared between the two slopes.

Overall, the Jaccard floristic similarity coefficient (Kj) between the north- and south-facing slopes was 0.11 – a very low value. Such pronounced differences in floristic composition over such a short distance are driven by contrasting ecological factors determining vegetation type. The primary factors include slope aspect, substrate, temperature regime, slope gradient, and biotic isolation.

The following plant associations were identified on the study area: **Rosetum varioherbosum** on the northern slope and **Bothriochloso-achnatheretum** on the southern slope.

On the northern slope, shade- and moisture-loving species predominate. Moisture is retained for extended periods and is actively utilized by plants for growth and development. On the southern slope, high temperatures, low humidity, and high evaporation rates cause rapid drying of vegetation.

Species richness per 100 m² on the southern slope is 36 units lower than on the northern slope. Vegetation cover on the southern slope is also less dense (10% lower), due to faster and prolonged soil warming, as well as steeper slope gradients promoting erosion.

In the 0–40 cm soil layer of different soil types at the Tsudakhar Station, distinct values of bulk density, moisture content, and C_{org} content and stocks were observed (Table 3).

Over the 10-year period on average, bulk density of mountain meadow-forest soils was lower than that of mountain meadow-steppe soils by 0.1 g/cm³ and 0.3 g/cm³ in the 0–20 cm and 20–40 cm layers, respectively.

Aridization on the south-facing slope at the Tsudakhar research station resulted in a 22.10% reduction in soil moisture content within the 0–40cm layer compared to the north-facing slope. These data indicate divergent patterns of erosion and moisture accumulation on slopes with contrasting aspects.

It is well established that in steppes and forest-steppes, uneven snowmelt on "warm" south- and west-facing slopes leads to significantly higher erosion rates than on "cold" north-facing slopes (Kireycheva and Shevchenko, 2020). This erosion reduces ecosystem productivity, which is closely linked to C_{org} stocks. Furthermore, south-facing slopes thaw earlier and remain unprotected for longer periods, increasing their vulnerability to erosion due to greater likelihood of rainfall runoff. However, under protected (reserve) conditions where erosion is absent, phytocenosis productivity on north-

Table 4. Net primary productivity of phytocenoses at the Tsudakhar Station (Intramountain Dagestan) during 2012–2021, n = 10.

Soil type, slope aspect, elevation above sea level	Aboveground biomass, t/ha	Root biomass, t/ha
Mountain meadow-forest soil, north-facing slope, 1160 m a.s.l.	27.35 ± 1.11	163.1 ± 4.15
Mountain meadow-steppe soil, south-facing slope, 1130 m a.s.l.	18.43 ± 1.51	98.68 ± 6.38

Table 5. Relationship between soil physical properties and soil organic carbon (C_{org}) stocks and phytocenosis productivity from 2012 to 2021. Correlation coefficients significant at $\alpha = 0.05$ are shown in bold.

Soil physical properties	Soil organic carbon stock	Aboveground biomass	Root biomass
North-facing slope			
Soil temperature	-0.815	-0.827	-0.580
Bulk density	-0.672	-0.713	-0.906
Soil moisture	0.707	0.709	0.606
South-facing slope			
Soil temperature	-0.857	-0.834	-0.773
Bulk density	-0.475	-0.758	-0.739
Soil moisture	0.821	0.850	0.852

facing slopes is not always higher than on south-facing slopes (Gasarov et al., 2016). Consequently, quantitative assessment of differences in phytomass productivity and C_{org} stocks between slopes of contrasting aspects is warranted.

Topographic heterogeneity in mountainous regions affects the redistribution of solar radiation, which significantly influences microclimate (air and soil temperature) (Burnett et al., 2008) and soil properties (organic matter content, chemical characteristics) (Lozano-García et al., 2015). Under protected conditions at the Tsudakhar station, C_{org} content in the 0–40 cm soil layer ranged from 1.42% to 2.11% (Table 3). C_{org} stock on the south-facing slope was 28.86 t/ha lower than on the north-facing slope. Thus, the highest C_{org} stocks were found in mountain meadow-forest soils.

In autumn, plant biomass returns to the soil, where it decomposes to form humus. However, on south-facing slopes, erosion-driven loss of plant material impedes the formation of a thick humus layer. Consequently, mountain meadow-steppe soils are poorer in C_{org} and less fertile compared to the mountain meadow-forest soils of north-facing slopes.

Grassland ecosystems occur across all natural-climatic zones and exhibit wide variability in botanical composition, sward density, and soil-ecological growing conditions, leading to considerable variation in their productivity. Grassland ecosystem productivity is determined and limited by numerous factors, including floristic composition, water regime, nutrient availability, and length of the growing season

(Broderick et al., 2022; Waheed et al., 2022). In our field study, phytocenosis productivity in the Inner Mountainous Dagestan region depended on soil type, slope aspect, and elevation (Table 4), as well as the resulting soil physical properties (Table 3).

The phytocenosis developed on mountain meadow-steppe soil of the south-facing slope accumulated less air-dry biomass: its productivity was 48.40% lower in aboveground biomass and 65.28% lower in root biomass compared to the phytocenosis on mountain meadow-forest soil of the north-facing slope.

Analysis of the relationship between soil physical properties and soil organic carbon (C_{org}) stocks as well as phytocenosis productivity indicators (aboveground biomass and root biomass), using Cheddock's scale, revealed a significant strong positive correlation with soil moisture and a pronounced strong negative correlation with bulk density and temperature (Table 5).

Conclusions

Physical properties of the slope soils differed significantly: over the 10-year period, the bulk density of the mountain meadow-forest soil (northern slope) was on average 0.1–0.3 g/cm³ lower than that of the mountain meadow-steppe soil (southern slope), while soil moisture was 22.10% higher.

Due to soil-climatic differences, C_{org} stocks on the northern slope were 1.5 times higher than on the southern slope.

Floristic diversity on the northern slope was 36 species greater; the Jaccard similarity coefficient between the northern and southern exposures was 0.11, indicating low species overlap.

As a result of climate aridization on the southern exposure, phytocenosis productivity declined by 48.40% in green biomass and 65.28% in root biomass.

A positive correlation was established between C_{org} accumulation and phytocenosis productivity with soil moisture, while negative correlations were found with soil bulk density and temperature.

The obtained results can inform the design of projects aimed at rational management of productive and destructive processes in natural and agrolandscapes. They also provide a foundation for remote sensing-based assessment of landscape productivity.

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