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ORIGINAL PAPER

ACCUMULATION OF ORGANIC CARBON IN SOIL UNDER VARIOUS TYPES OF HIGHLAND TEMPERATE MEADOWS*

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Abstract

The aim of the study was to determine the content of soil organic carbon (SOC) in various types of highland temperate meadows. The analysis covered 360 soil samples collected in 6 types of meadows in SE Poland. Meadows were grouped on the basis of the analysis of phytosociological records taken according to the Braun-Blanquet method. In the laboratory, pH in 1 mol dm^{-1} KCl solution, organic C content by the Tiurin method, general N form by the Kjeldahl method, and assimilable P and K forms by the Egner-Rhiem method were determined. In the calculation of SOC in kg ha^{-1}, the 0-30 cm profile layer was analyzed, assuming an average soil weight equal to 10^3 kg m^{-3}. Analyses showed that the SOC content significantly depended on the type of meadow (moisture, plant species composition), pH, N and P content, but no relationship with K was found. The average content of SOC varied depending on the type of meadow from 22.1 to 172.4 g kg^{-1} (66.44-517.35 kg 10^3 ha^{-1}), with the highest value being in rush meadows, and the lowest – in psammophilic meadows. The total SOC stock estimated at work for the studied types of upland meadows (30921 ha) in SE Poland is 11.33 kg 10^9. The correlation of SOC with pH is positive, with easily discernable limits determined by 3.5 and 7 pH values, beyond which, in all tested meadows, the carbon content in the soil does not exceed 100 g kg^{-1}. SOC is also positively correlated with the content of N and P in the soil. We have proven that the diverse habitat conditions of meadow ecosystems have an impact on the accumulation of organic carbon in the soil. It is necessary to consider the possibility of taking protective measures for these ecosystems of meadows in the temperate climate, which are characterized by the highest SOC accumulation. The implementation of such measures could positively affect the struggle against global warming, while preserving the mosaic landscape of fields, meadows and forests characteristic for this region.

Keywords: soil organic carbon (SOC), sequestration, agriculture, grassland ecosystem, meadow.

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INTRODUCTION

Organic carbon contained in soil fulfills a number of important tasks, for example it contributes to the improvement of soil quality and water purity, which is reflected in improving the quality of food production. It also effects an increase in yields, which entails an improvement of food safety, enhancing food security, while reducing CO_2 emissions in the atmosphere (Eswaran et al. 1993, Lal 2004). Recently, the latter effect has gained particular importance, as it is considered to be useful in the fight against global warming (Dorrepaal et al. 2009, Fornara et al. 2011). The exchange of carbon between the atmosphere and ecosystems takes place continuously, and the soil is the most important link in this cycle. It is estimated that the amount of carbon accumulated in soils is twice as large as the amount of carbon contained in the atmosphere, and in the case of organic carbon it amounts to 1.460-1.550 kg 10^{15} (Batjes 2014). However, the results of long-term research on grasslands in Tibet indicate that the rate of carbon exchange between mountain meadow ecosystems and the atmosphere in 1990-2000 increased in comparison with the period before 1990 (Zhang et al. 2007). These results are confirmed by Gill et al. (2002), who found that the binding of atmospheric CO_2 in the soils of meadow ecosystems at the beginning of the 21st century was significantly lower than in the previous century. In both cases, these changes are associated with global warming. The increase in average air temperatures also causes an increase in average soil temperatures, which according to Melillo et al. (2002) influences the change in the composition and activity of soil microbes, and this in turn reduces the sequestration of carbon in soil. However, studies carried out in the years 2002-2011 on the alpine grasslands of the Tibetan Plateau indicate that SOC stocks increased during the period considered at a general rate of 4.66 g m^{-2} yr^{-1}, with the exception of dry alpine steppes, which showed a loss of C – 11.9 g m^{-2} yr^{-1} (Chen et al. 2017).

The rate and level of carbon sequestration in soil depends not only on climatic conditions (Melillo et al. 2002, Doetterl et al. 2015) but also on the way land is used (Sleutel et al. 2003, Singh et al. 2007, Tobiašová 2015, Ma et al. 2016) and the type of plant cover (Wasak, Drewnik 2015, Drewnik et al. 2016). The results of extensive research conducted in northern Belgium in 1989-2000 allow one to conclude that the accumulation of carbon in soils used intensively is at a very low level, which gives only a very modest contribution to the state's effort to reduce greenhouse gas emissions (Sleutel et al. 2003). Singh et al. (2007), when conducting research in India covering the years 1975-2002, also found that intensive agricultural cultivation in arid regions affects the reduction of organic carbon content in soil. Similar trends can be noticed in meadow ecosystems. Grazed meadows in the Tibetan Plateau accumulate much less SOC than those abandoned for at least 5 years. SOC stocks on pasturage areas were reduced by 33% (Ma et al.

2016). Taking into account various forms of land use: forest ecosystem, meadow ecosystem, agro-ecosystem, we can state that the highest total organic carbon content occurs in soils of forest ecosystems, less organic carbon appears in meadow ecosystems, and the lowest amount is found in agricultural ecosystems (Tobiašová 2015). This is confirmed by Wasak and Drewnik (2015), who determined the SOC content in soils under larch forest at 63.5 kg 10^3 ha^{-1}, while in soil under grassland it fell to 47.5 kg 10^3 ha^{-1}. In turn, Berninger et al. (2015) conducting research on the European mountain meadows and rangelands, and Ahmed et al. (2012) studying agroforestry systems in Slovakia found that SOC carbon resources in the soils of meadow ecosystems are high and comparable with forest ecosystems.

We hypothesized that the varied habitat conditions of meadow ecosystems have an impact on the accumulation of organic carbon in the soil. We paid special attention to the humidity of the habitats, and to the species composition of plants classifying the meadows belonging to a certain type and pH.

The aim of the study was to determine the content of organic carbon in soil (SOC) in various types of highland temperate meadows.

MATERIAL AND METHODS

Study area

The research was conducted from June to September in 2010-2018 in various types of upland meadows, in diversified conditions of soil moisture, pH and abundance in selected macroelements (NPK). The research area (Figure 1) included fragments of the Central Poland and Carpathian Foothills (SE Poland; 49.5626-50.4048° N, 21.4815-22.8713° E). In the southern part of the study area, there are hills stretching from northwest to southeast, with altitudes up to 350 m above sea level. It is dominated by brown, clayey and Flysch rendzina soils formed from silt, and Histosols in the river valleys. The duration of the growing season varies from 210 to 225 days, and the average annual rainfall is from 700 to 800 mm. In the central and northern part, the largest area is occupied by plains lying at an altitude of 220-250 m a.s.l. In this area, there are brown, alluvial and swampy soils. The average annual rainfall is 600-700 mm, and the growing season lasts 220-225 days.

Phytosociological records

Phytosociological records (455 records) were taken using the Braun-Blanquet method. MULVA-5 software was used. Records were subjected to hierarchical numerical classification and then qualified for individual habitats on the basis of species composition, location of the studied meadow

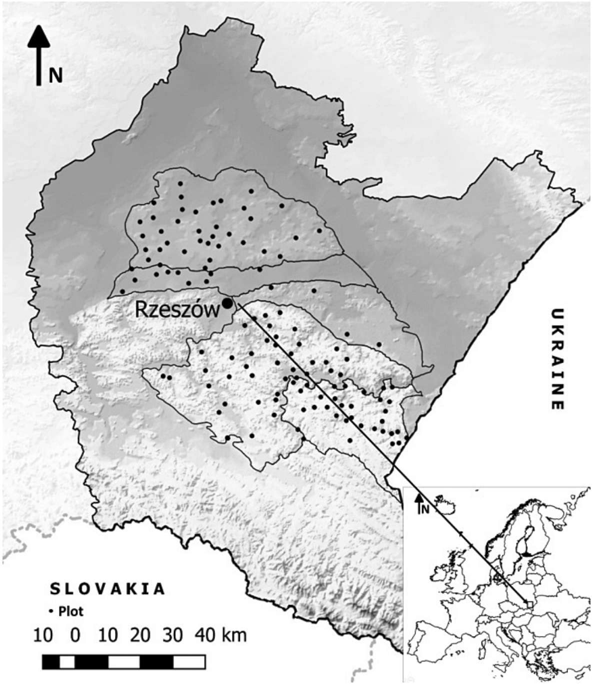

Fig. 1. Area of research

and soil type. As a result of these studies, 360 records remained, while the others were excluded due to the lack of any unambiguous classification for a given type of meadow. On the basis of characteristic and distinguishing species, 6 habitats were distinguished, to which 60 phytosociological records were assigned: fresh meadows on drier soils, less rich in nutrients (A), *Agrostis capillaris, Festuca rubra* and *Anthoxanthum odoratum*; fresh meadows on fertile, optimally moist soils (B), *Arrhenatherum elatius, Trisetum flavescens, Festuca pratensis, Poa pratensis* and *Dactylis glomerata*; periodically wet meadows (C), *Cirsium rivulare, Scirpus sylvaticus* and *Alopecurus pratensis*; constantly flooded rush meadows (D), *Phalaris arundinacea, Phragmites australis, Glyceria maxima, Typha angustifolia* and *Acorus calamus*; xerotermic grasslands on dry soils with high pH (E), *Brachypodium pinnatum, Salvia verticillata, Filipendula vulgaris* and *Plantago media*; psammophilic grasslands on acidic and dry soils (F), *Corynephorus canescens, Nardus stricta, Festuca ovina* and *Danthonia decumbens*.

Soil sampling and laboratory analyses

At each site where phytosociological records were collected, a soil sample was taken from the 0-30 cm layer in six replicates, to make a composite sample, which was then analyzed. The pH in 1 mol dm^{-1} KCl solution, the organic C content with the Tiurin method, the general N form by the Kjeldahl method, and the assimilable forms of P and K with the Egner-Rhiem method were determined. The organic C content per 1 ha was calculated, assuming than an average soil weight equal 10^3 kg m^{-3}. The 0-30 cm profile layer was taken into account in the calculation of SOC in kg ha^{-1}. The SOC stock in individual types of meadows in south-eastern Poland was computed as the product of the area occupied by a given type of grassland and the average SOC content in kg ha^{-1} calculated for the given type of a meadow. The area of grassland was estimated on the basis of a land use database from the SE Poland municipalities. Since soil density was not tested, only the average value was considered, same for all 6 types of meadows, while the results for SOC mass per unit area were an estimate.

Statistical analysis

For some of the meadow types investigated, preliminary analyses showed lack of the SOC normality distribution (quantitative feature, independent variable). Moreover, the types of meadows are a qualitative feature (a grouping variable). Therefore, the data analysis was carried out using non-parametric tests: Spearman test, Kruskal-Wallis correlation with the median test, and *U* Mann-Whitney test. Statistical significance was defined as $P<0.05$. All analyses were performed with Statistica 12 software.

RESULTS AND DISCUSSION

The Spearman's rank correlation coefficient (r = -0.4231) indicates a significant relationship between the meadow type and the content of soil organic carbon, the correlation here is moderate (Table 1). This is also well seen in Figure 2. The largest amount of organic carbon is deposited

Table 1

Spearman correlation coefficient

Variable	Type of meadows	pH in 1mol dm^{-1} KCl	N_{tot}	P	K
SOC	-0.4231*	0.3039*	0.5549*	0.1314*	0.0152

* Significant at 0.05 level.

in the soils of rush meadows (D), the habitat that is constantly overly moist, characterized by having fertile soils (Table 2). The SOC content here, depending on the site (60 meadows), was from 56.0 to 389.0 g kg^{-1}, with an average of 172.4 g kg^{-1} (Table 2). On average, 14% less SOC is accumulated in the soils of periodically wet meadows (C), and fresh meadows with fertile soils (B) have 29% less SOC than rush meadows (D). In the case of fresh meadows with poor soils (A), the SOC content in the soil is lower than in the D-type meadow by as much as 68%. Even less carbon is found in the soils

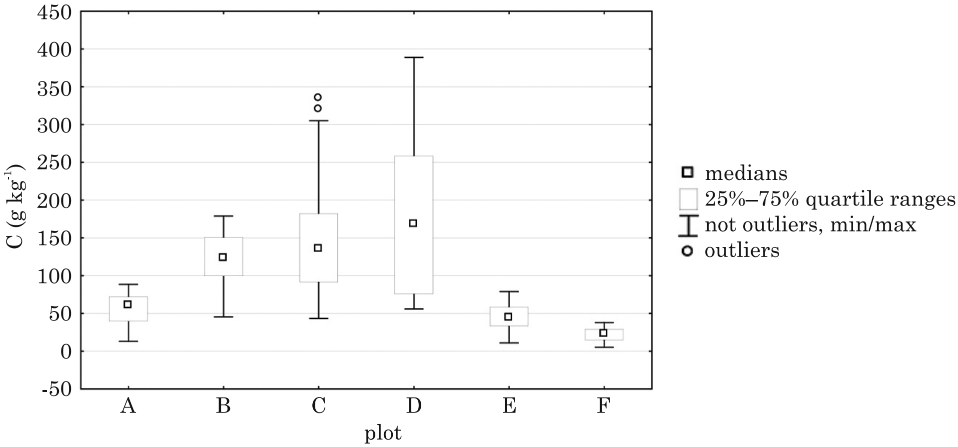

Fig. 2. The content of organic carbon SOC in soils under various types of meadows, elements of descriptive statistics; A-F – see Table 1

Table 2

The content of SOC carbon and macroelements in soil of the studied types of meadows

Type of meadows/*n*	pH in 1 mol dm^{-1} KCl	Average content of macroelements in soil (mg kg^{-1})			SOC (g kg^{-1})			SOC (kg 10^3 ha^{-1})
		N_{tot}	P	K	min.	max.	average	average
A/60	4.3	11.8	20.9	82.6	12.7	88.5	56.1	168.24
B/60	5.2	14.1	25.8	101.4	45.5	179.0	122.4	367.10
C/60	5.4	12.0	23.1	97.7	43.5	335.0	148.7	445.99
D/60	5.3	17.8	25.1	86.7	56.0	389.0	172.4	517.35
E/60	6.8	8.9	27.5	164.8	11.0	79.0	45.5	136.55
F/60	4.0	5.6	14.4	75.8	5.3	38.0	22.1	66.43

A – optimally moist habitat, poor soils, fresh meadows, B – optimally moist habitat, fertile soils, fresh meadows, C – periodically excessively moist habitat, fertile soils, periodically wet meadows, D – permanently excessively moist habitat, fertile soils, rush grasslands, E – dry, alkaline habitat, low fertile soils, xerothermic grasslands, F – Dry, acidic habitat, poor soils, psammophilic (grasslands)

of xerothermic meadows (E): 45.5 g kg^{-1}, which is 74% less than the calculated highest value for meadows D. The least organic carbon is accumulated in sandy pinewood (F) meadows: 87% less than meadows D. The average SOC content per unit area fluctuated, depending on the type of meadow, from 66.43 to 517.35 kg 10^3 ha^{-1} (Table 2). Such high averages translated into the total SOC stock in particular types of Polish upland meadows in Poland (Table 3). The total SOC stock estimated herein for the studied types of upland meadows in SE Poland is 11.33 kg 10^9, which is 3.46% of the annual CO_2 emissions by Poland (according to Global Carbon Atlas in 2017 Poland emitted 327 kg 10^9 CO_2 to the atmosphere).

Table 3

SOC stock in the ecosystems of the upland meadows of SE Poland

Type of meadows	Area of meadows (ha)						SOC (kg 10^9)
	Kolbuszowa Plateau	Podkarpacka ice-marginal valley	Rzeszowskie foothills	Dynowskie foothills	Przemyskie foothills	total	
A	1089	816	785	3075	738	6503	1.094
B	1089	816	1178	4612	711	8406	3.086
C	3266	1224	1178	1537	178	7383	3.293
D	4355	1020	785	1025	89	7274	3.763
E	0	0	0	0	62	62	0.008
F	1089	204	0	0	0	1293	0.086

A significant relationship, although weaker, was also noted for the SOC content depending on the pH – the Spearman's correlation coefficient here was 0.3039, indicating a low correlation. Although this is not confirmed by the coefficient of determination (Figure 3), this correlation only explains about 5% of cases. However, the limits determined by pH = 3.5 and 7 are well visible here, except for the ones where the total carbon content in the soil does not exceed 100 g kg^{-1}.

A statistically significant relationship was also noted for the amount of SOC depending on the N content in the soil. The Spearman's correlation coefficient was 0.5549, which indicates a moderate correlation. In general,

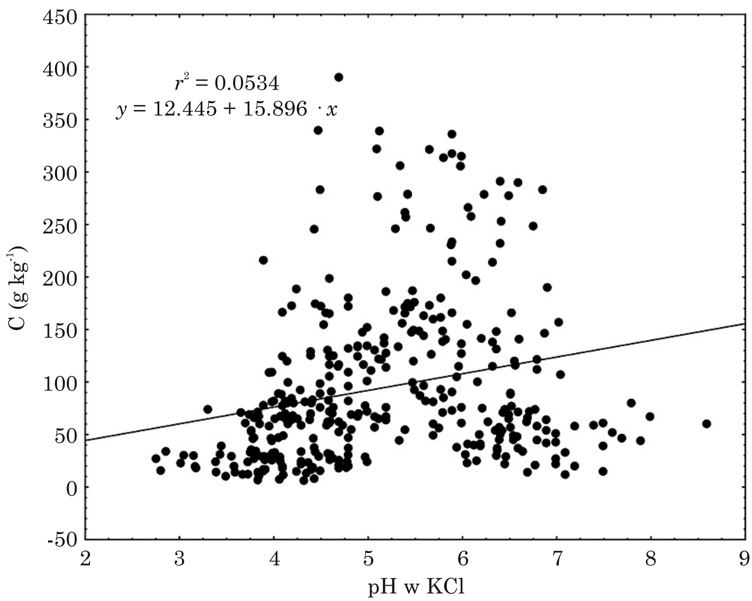

Fig. 3. Correlation of SOC with pH in KCl

the growth in nitrogen in the soil is accompanied by the SOC content increase. The highest average N 17.8 mg kg^{-1} content was recorded under the same type of meadow (D) as for the highest average SOC content. On the remaining meadow types, the N content ranged from 5.6 (F-type meadows) to 14.1 mg kg^{-1} (B-type meadows) – Table 2. A weak correlation (r = 0.1314) was determined for the SOC and P content in soil. The content of P in soil was from 14.4 (F) to 27.5 mg kg^{-1} (E). However, there is no correlation for SOC and the K content in soil. The content of K in the soil ranged from 75.8 (F) to 164.8 mg kg^{-1} (E; Table 2).

The results of the Kruskal-Wallis test and the median confirm statistically significant differences in the accumulation of organic carbon SOC in various types of meadow ecosystems (Tables 4 and 5). Therefore, SOC depends significantly on the type of meadow that grows on this soil. Then, in order to find out between which groups of meadows there are statistically significant differences in the accumulation of organic carbon in the soil, the Mann-Whitney U test was carried out (Table 6). The results of this test allow us to conclude that these differences are observed between all groups of meadows with the exception of: C and D as well as B and C. In these two

Table 4

Median test results

Dependent: SOC (g kg^{-1})	Median test, general median = 69,000; SOC (g kg^{-1}) Independent variable (grouping): plot Chi square = 198.7284 df = 5 p = 0.000						
	A	B	C	D	E	F	total
<= medians: observed	41.00	6.00	8.00	12.00	54.00	60.00	181.00
Expected	30.17	30.17	30.17	30.17	30.17	30.17	
Observed- expected	10.83	-24.17	-22.17	-18.17	23.83	29.83	
> medians: observed	19.00	54.00	52.00	48.00	6.00	0.00	179.00
Expected	29.83	29.83	29.83	29.83	29.83	29.83	
Observed- expected	-10.83	24.17	22.17	18.17	-23.83	-29.83	
Total: observed	60.00	60.00	60.00	60.00	60.00	60.00	360.00

Table 5

Results of the Kruskal-Wallis test

Dependent: SOC (g kg^{-1})	Kruskal-Wallis test: H (5, N = 360) = 251.1447 p = 0.000		
	N valid	range sum	mean range
A	60	8405.00	140.08
B	60	15277.00	254.62
C	60	15746.00	262.43
D	60	16244.50	270.74
E	60	6623.00	110.38
F	60	2684.50	44.74

Table 6

Results of the Mann-Whitney U test

Type of meadows	Sum of rang		Z	p
	1	2		
1A : 2B	2045.50	5214.50	-8.31	0.00
1C : 2D	3440.50	3819.50	-0.99	0.32
1E : 2F	4982.00	2278.00	7.09	0.00
1A : 2C	2187.50	5072.50	-7.57	0.00
1A : 2D	2248.50	5011.50	-7.25	0.00
1A : 2E	4220.00	3040.00	3.09	0.00
1A : 2F	5023.50	2236.50	7.31	0.00
1B : 2C	3371.50	3888.50	-1.35	0.18
1B : 2D	3243.50	4016.50	-2.03	0.04
1B : 2E	5337.50	1922.50	8.96	0.00
1B : 2F	5430.00	1830.00	9.44	0.00
1C : 2E	5234.50	2025.50	8.42	0.00
1C : 2F	5430.00	1830.00	9.44	0.00
1D : 2E	5287.00	1973.00	8.69	0.00
1D : 2F	5430.00	1830.00	9.44	0.00

cases differences in carbon accumulation in the soil are statistically insignificant. In the case of C and D meadows, the average content of organic carbon in the soil was 14%, and in the case of B and C meadows the value was 17%.

The average SOC content varied depending on the type of meadow from 66.43 to 517.35 kg 10^3 ha^{-1} (Table 2), with the highest value being achieved for rush meadows (D) and the lowest value – for psammophilic meadows (F). However, the average SOC content of agriculturally used soil for Poland is 79.6 kg 10^3 ha^{-1}, which is higher than in Bulgaria (28 kg 10^3 ha^{-1}), Slovakia (45 kg 10^3 ha^{-1}) and Italy (56 kg 10^3 ha^{-1}), and lower than in Denmark (86 kg 10^3 ha^{-1}) and the Netherlands (100 kg 10^3 ha^{-1}) – Lugato et al. (2013). Therefore, the research shows that most types of upland meadows (except for psammophilic meadows) accumulate much higher amounts of C in the soil, under the same conditions of temperate climate, than soils used for agriculture. The moderate SOC values obtained in the ecosystem of highland meadows are even higher than the estimated SOC values for forest ecosystems in the temperate forest zone: 137 kg 10^3 ha^{-1} (Dincă et al. 2012), 11-149 kg 10^3 ha^{-1}, depending on the type of forest site and depth (Zwydak et al. 2017). However, the results of research conducted in Japanese forest soils (temperate, subtropical and tropical climate zones) show that the SOC content varied from 82 to 330 kg 10^3 ha^{-1} (Morisada et al. 2004). The upper range of the SOC content in Japanese forest soils is higher than in meadows type A, E and F, comparable to B type meadows, but still lower than in C and D meadows (Table 2).

The content of SOC from 22.1 to 172.4 g kg^{-1} (66.43-517.35 kg 10^3 ha^{-1}) achieved in this research is higher than the results published by Tobiašová (2015) for highland meadows in the temperate climate in Slovakia – SOC = = 8.6-20.1 g kg^{-1} (26-60 kg 10^3 ha^{-1}), depending on the type of soil. Drewnik et al. (2016) estimated SOC for subalpine meadows in the Eastern Carpathians from 46 to 117 kg 10^3 ha^{-1}. In turn, Yimer et al. (2006) calculated the SOC value for grasslands in the mountains of Ethiopia at the level of 100-240 kg 10^3 ha^{-1}. Lal (2004) assumes the SOC value varying from from 30 kg 10^3 ha^{-1} in areas characterized by dry climate up to 800 kg 10^3 ha^{-1} in cold regions. However, Zhao et al. (2014) gives the average value of organic carbon in soil of central China at 5010 mg kg^{-1}, which can be converted to 15 kg 10^3 ha^{-1}. Even higher SOC values, i.e. 11 000 mg kg^{-1}, 33 kg 10^3 ha^{-1}, are given for northern China by Liu et al. (2017).

This study found a correlation between the content of N in soil and SOC. A similar relationship was presented by Nedvěd et al. (2008), except that they showed a strong relationship between the content of N and SOC. In both cases, a positive correlation was recorded.

CONCLUSIONS

This research provides new information on the accumulation of SOC in the soils of highland temperate meadows. The novelty of our study lies in the distinction, based on the species composition, of several types of grasslands for which the SOC content was determined separately; in contrast, until now the SOC content has been determined for grassland ecosystems without any division into meadow types. The current results show statistically significant differences in the content of organic carbon in soil under various types of meadows. Meadows periodically wet (C) and rush meadows (D) accumulate large amounts of carbon in soil, on average 148.7 and 172.4 g kg^{-1}. These values significantly exceed the average values for arable land and forest ecosystems of temperate climate. Agricultural abandonment of meadows, which often took place in the studied area, certainly had an impact on such high stocks of organic carbon in the soil, as research from other regions of the world confirms (Ma et al 2016). In turn, soils under psammophilic grasslands accumulate only 22.1 g kg^{-1} of organic carbon. We have proven that the diverse habitat conditions of meadow ecosystems, in particular the humidity of habitats, the plant species composition which classified meadows into a specific type, and soil pH have an impact on the accumulation of organic carbon in soil. It is necessary to consider the possibility of taking protective measures for these ecosystems of temperate meadows in the temperate climate, which are characterized by the highest SOC accumulation. The implementation of such measures could positively affect the struggle against global warming, while preserving the mosaic landscape of fields, meadows and forests characteristic for this region.

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