www.czasopisma.pan.pl PAN www.journals.pan.pl

JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2022.141556
2022, No. 54 (VII–IX): 68–76

The content and stock of organic carbon in the soils of grasslands in Poland and the possibility of increasing its sequestration

Stefan Pietrzak, Jakub T. Hołaj-Krzak

Institute of Technology and Life Sciences – National Research Institute, Falenty, 3 Hrabska Avenue, 05-090 Raszyn, Poland

RECEIVED 28.09.2021 ACCEPTED 09.03.2022 AVAILABLE ONLINE 28.09.2022

Abstract: The aim of the study was to recognise the accumulation of organic carbon (SOC) in the soils of Polish grasslands (GL) and to consider the possibility of increasing its sequestration in these soils. The Tiurin method (mineral soils) and the mass loss method (soil of organic origin) were used. It was found that: (i) the average SOC content of mineral soils is 2.44% and of organic soils – 10.42%; (ii) according to the Polish criteria, approximately 84% of GL mineral soils are classified as classes with high and very high SOC content, and over 15% and 1% – in classes with medium and low SOC content, respectively; more than 99% of organic soils belong to two classes with the highest SOC content and less than 1% to the class with an average content; (iii) according to the European Soil Bureau, the share of GL mineral soils with a high SOC content is slightly over 4%, medium – slightly over 47%, and low and very low – around 50%; for organic soils they are 67, 29, and 4%, respectively; (iv) the reserves of organic carbon in the 0–30 cm layer on the entire surface of GL soils amount to 412.7 Tg of SOC. There is considerable scope for increasing the SOC stock in meadow-pasture soils.

Keywords: grassland, management practices, organic carbon content, organic carbon stock, organic carbon sequestration, soils

INTRODUCTION

Grassland (GL) soils are characterised by a high content of organic matter (SOM), which provides plants with nutrients, increases soil aggregation and reduces soil erosion, as well as increases cation exchange and water retention capacity [Conant *et al.* 2001]. The reserves of organic matter in permanent grassland soils are usually much greater than in cultivated soils on arable land (AL). In the Dutch conditions, it was found in this respect that the multiplicity of the SOM level between the mentioned soil types may be from 2 to 5 [Batjes 1999]. The formation of large amounts of organic matter in GL soils is favoured by their permanent plant cover, due to the fact that it is characterised by a high ability to accumulate CO_2 from the atmosphere (in the process of photosynthesis), which translates into the level of biomass production and the amount of plant residues formed from it returning to the soil, and the turf process (as a result, the topsoil is enriched with organic matter) [Sapek 2009]. Looking from a different point of view, the greater accumulation of organic matter in GL soils as compared to arable land is favoured by the fact that they are generally not subject to mechanical cultivation operations disturbing their structure. For this reason, they lose less organic carbon, which is the main component of organic matter. As a result, large amounts of organic carbon gradually – in the long term – accumulate in the soils of grasslands [Jones 2010]. Considering the issue of the formation of organic matter in GL and AL soils, it is important to emphasise that soil microorganisms play a key role in its formation [Louis *et al.* 2016], although their role in this regard has not yet been sufficiently understood [Jiang *et al.* 2021]. The soils of grasslands, compared to soils of arable lands, have a higher level of carbon in the biomass of microorganisms (carbon in microbial biomass is a measure of the content of C in living components of soil organic matter, i.e. in bacteria and fungi) per unit of organic carbon in the soil [McGonigle, Turner 2017]. This suggests that from the microbiological point of view, the process of building organic matter in both types of agricultural land is different.

Grassland soils due to its natural properties to accumulate a large amount of organic matter, and thus organic carbon, grassland soils are considered as an important factor in compensating carbon dioxide emissions and mitigating climate change [Godde *et al.* 2020; O'Mara 2012; Paulsen 2020; Tessema *et al.* 2020; Whitehead 2020]. It is estimated that up to 30% of the world's SOC stock is stored in grassland soils down to a depth of 1 m, and these resources could still be increased as they have been lost over large areas in the past by a number of processes such as soil structure destruction, degradation of vegetation, fires, erosion, nutrient deficiency and water scarcity [Lorenz, Lal 2018]. The soils of degraded grasslands have a very high potential for carbon sequestration (i.e. removing CO_2 from the atmosphere and storing it in the soil via meadow sward) [Yu *et al.* 2020]. Possibilities of using this potential are created, in particular, by activities aimed at increasing yields from GLs through the use of fertilisers and irrigation, improving the species composition of sward (using high-yield and legume mixtures), and activities involving the rehabilitation of degraded meadows and pastures, as well as minimising the negative effects of grazing [Conant 2010; Conant *et al.* 2017; Epple *et al.* 2016].

Permanent GLs in Poland cover over 3.1 mln ha, i.e. 21.3% of the agricultural land area [GUS 2020]. Their soils constitute a very large reservoir of organic carbon, and there are significant opportunities to increase it through GL renovation, due to the fact that, as it is estimated, over 50% of them are degraded (which results in low yields) [Barszczewski *et al.* 2015]. In the near future, an important impulse to increase organic carbon in grassland soils may be the "Farm to Fork" strategy adopted by the European Commission as part of the European Green Deal which, among others, supports and recommends the development of carbon dioxide-absorbing crops as a new business model for farmers [Communication … 2020].

The problem of storing and shaping organic carbon stock in the soils of grasslands in Poland is not sufficiently recognised in the quantitative dimension. Given the importance of grassland in mitigating climate change and the practical challenges it presents, there is a need to fill this gap. An attempt to eliminate it was made in this study. It aims to identify the state of organic carbon content and stock in the top layer of grassland soils in Poland, and to analyse the possibility of increasing its sequestration in these soils.

MATERIALS AND METHODS

DATA ORIGIN AND LOCATION OF SAMPLING POINTS

The research on the content of organic matter and organic carbon in the soils of GLs in Poland was carried out as part of the soil and water monitoring system conducted by the National Chemical-Agricultural Station (Pol. Krajowa Stacja Chemiczno-Rolnicza, KSChR) and regional chemical and agricultural stations, in cooperation with the Institute of Technology and Life Sciences (now Institute of Technology and Life Sciences – National Research Institute, Pol. Instytut Technologiczno-Przyrodniczy – Państwowy Instytut Badawczy, ITP – PIB) [Pietrzak 2012a, b]. The subject of the research were soil samples from 860 checkpoints of grassland soils throughout Poland, of which 703 were located on mineral soils and 157 on organic soils – Table 1. The location of soil sampling sites took into account the spatial differentiation of the occurrence of grasslands in Poland (Fig. 1). The soil material for laboratory analyses was obtained mainly in

Table 1. The number of monitoring points for grassland soils

Type of soil	The number in Poland and voivodeship																
	Poland	Lowe Silesia	Kuyavia-	Pomeranian	Lublin	Lubusz	Łódź	Lesse Poland	Masovian	Opole	Subcarpathian	Podlaskie	Pomeranian	Silesian	Świętokrzyskie	Warmian-Masurian	Greater Poland
Mineral	703	43	19	38	26	34	62	106	15	53	67	25	39	34	57	50	35
Organic	157	–	11	4	9	9	1	19	–	–	37	18	1	–	31	9	8
Total	**860**	**43**	**30**	**42**	**35**	**43**	**63**	**125**	**15**	**53**	**104**	**43**	**40**	**34**	**88**	**59**	**43**

Source: own elaboration based on the National Chemical-Agricultural Station results.

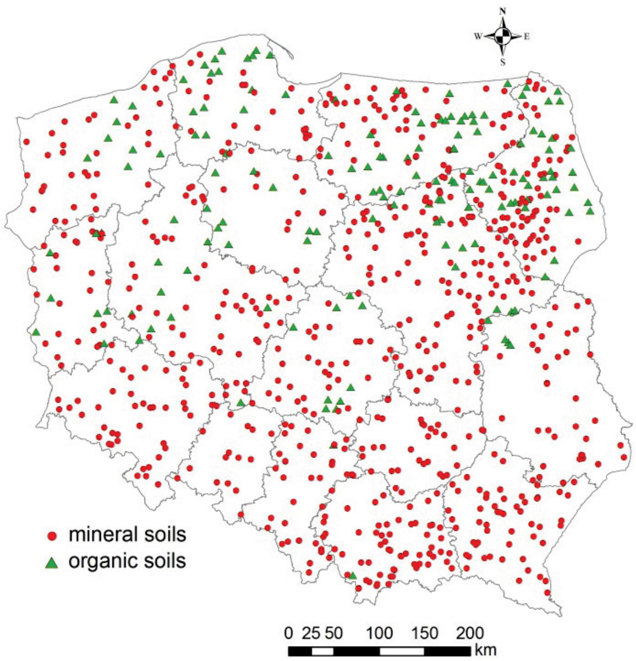

Fig. 1. Location of soil sampling sites in grasslands in Poland for the determination of organic carbon [Nawalany 2021]

2008 (812 samples) and a small part in several other years (36 samples were obtained in 2006, in 2013 – 1, in 2016 – 4, in 2017 – 3, in 2018 – 1, in 2019 – 3).

METHODS

Soil samples for testing were taken from the 30 cm deep top soil layer. In soil samples of organic origin, the content of organic matter (OM) was determined using the weight loss method on calcination at 550°C for 7 h (weight loss during calcination was taken as the content of organic matter) [IUNG 1983]. The percentage of organic content was calculated as the ratio of the weight of the dried sample to the constant weight before and after burning (calcining). On the basis of the determined content of organic matter, the amount of organic carbon (SOC, %) in the tested samples was calculated by dividing the obtained OM value (%) by the van Bemmelen coefficient, amounting to 1.724 [Łądkiewicz *et al.* 2017]. The organic carbon content was determined by the Tiurin method in the samples of mineral soils. The Tiurin method was applied to soil samples with an organic matter content of up to 15%, because above this OM value in the soil the mentioned method does not give "reliable results, due to the difficulty of fully burning large amounts of organic carbon" [Fajer 2014]. The obtained test results were classified based on the existing Polish and European criteria for assessing the organic carbon content in soils – Table 2 – and was used to determine the abundance of soils in this component in the 0–30 cm layer, in relation to the area of 1 ha of grassland (in kg·ha^{-1}).

Table 2. Criteria for assessing the content of organic carbon (SOC) in the soils of Poland and Europe

Content class	Classification by IUNG – PIB		Classification by EDS	
	organic matter content	organic carbon content	organic matter content	organic carbon content
	%			
Very low	–	–	<1.72	<1.0
Low	<1.0	<0.58	⟨1.72–3.45)	⟨1.0–2.0)
Medium	⟨1.0–2.0)	⟨0.56–1.16)	⟨3.45–10.34)	⟨2.0–6.0)
High	⟨2.0–3.5)	⟨1.16–2.03)	≥10.34	≥6.0
Very high	≥3.5	≥2.03	–	–

Source: own elaboration based on Kuś [2015] and Pikuła [2015].

Soil resources of organic carbon were calculated from the Equation (1) [Crème *et al.* 2012; Kuś 2015; Tessema *et al.* 2020]:

$$Z_{\mathrm{C_{org}}} = \mathrm{SOC} \cdot y \cdot h \cdot 1000 \tag{1}$$

where: Z_{Corg} = organic carbon resources in the 0–30 soil layer (kg·ha^{-1}), SOC = organic carbon content in the 0–30 cm soil layer (%), y = soil density (kg·dm^{-3}), h = thickness of the soil layer (cm).

The bulk density of mineral soils was adopted after Fotyma *et al.* [2010] – Table 3.

Table 3. The bulk density of mineral soils depending on their agronomic category

Agronomic category of soils	The proportion of floating particles in diameter <0.02 mm (%)	Soil density (kg·dm^{-3})
Very light (VL)	≤10	1.533
Light (L)	(10–20⟩	1.500
Medium (M)	(20–35⟩	1.416
Heavy (H)	>35	1.300

Source: own elaboration based on Fotyma *et al.* [2010].

The density of organic soils was determined using the Equation (2) [Pietrzak 2015]:

$$y = -0.000006\ OM^3 + 0.001\ OM^2 - 0.06235\ OM + 1.6346 \quad (R^2 = 0.9489) \tag{2}$$

where: y = soil density (kg·dm^{-3}), OM = the content of organic matter in the soil (%).

The obtained results were also statistically processed. In this regard:
- descriptive statistics of the sets of results for determination of organic carbon content in soil samples were performed, calculating their arithmetic means and coefficients of variation (CV);
- an analysis of the r-Pearson correlation between the average SOC content in the soil and the cattle density in the voivodeships was carried out;
- the significance of differences between the average SOC contents in various categories of mineral soils was determined using the Kruskal–Wallis test.

The collection of grassland soil samples and their laboratory tests (in own accredited laboratories) were carried out by regional chemical and agricultural stations. The results of the determinations were collected in a database maintained by the KSChR. The results of laboratory determinations were processed at ITP – PIB Falenty on the basis of data provided by the KSChR.

RESULTS

ORGANIC CARBON CONTENT IN GRASSLAND SOILS

In the analysed research period, the average content of organic carbon (SOC) in the mineral soils of grasslands in Poland, in relation to their top 30 cm layer, was 2.44% – Table 4. Among the various categories of mineral soils, the highest amounts of SOC were found in light soils, and the lowest in medium soils.

In individual voivodeships, the average content of SOC in the mineral soils of GL oscillated between 1.79 and 3.81%, wherein the populations of the results on the basis of which it was determined were characterised by high variability – Table 5. This indicates a large natural variation (e.g. grain size, topography and water relations) and anthropogenic (management practices) factors influencing the content of organic matter in various regions of Poland and in their area.

In the case of organic soils of grasslands, the national average content of organic carbon in the 0–30 cm layer was

Table 4. Organic carbon (SOC) content in mineral soils of grasslands in Poland in the 0–30 cm layer

Type of soil	Number of samples	SOC content average	min	max	Standard deviation
		%			
Total mineral	703	2.44	0.26	8.64	1.50
Very light	204	2.48	0.26	8.64	1.57
Light	191	2.54	0.48	7.96	1.60
Medium	216	2.31	0.58	7.49	1.42
Heavy	92	2.46	0.41	7.12	1.31

Source: own study based on the results of National Chemical-Agricultural Station.

Table 5. The average content of organic carbon (SOC) in the 0–30 cm layer of mineral soils of grasslands in individual voivodeships and on the scale of the entire country

Voivodeship	Number of samples	SOC content average	min	max	Standard deviation
		%			
Lower Silesia	43	2.25	0.73	4.41	1.00
Kuyavian-Pomeranian	19	3.09	0.79	6.79	1.88
Lublin	38	1.92	0.59	4.51	0.96
Lubusz	26	2.69	0.41	8.64	1.93
Łódź	34	2.04	0.69	5.49	1.21
Lesser Poland	62	1.90	0.58	4.19	0.73
Masovian	106	2.46	0.56	7.49	1.54
Opole	15	2.15	0.72	5.83	1.37
Subcarpathian	53	1.79	0.26	4.35	0.89
Podlaskie	67	3.81	0.69	7.96	2.04
Pomeranian	25	2.58	0.94	5.90	1.45
Silesian	39	1.99	0.30	4.00	0.79
Świętokrzyskie	34	1.69	0.59	4.71	0.96
Warmian-Masurian	57	3.06	0.76	7.26	1.80
Greater Poland	50	2.46	0.48	6.63	1.55
West Pomeranian	35	2.61	1.11	4.98	0.93
Poland	**703**	**2.44**	**0.26**	**8.64**	**1.50**

Source: own study based on the results of National Chemical-Agricultural Station.

10.42% – Table 6, i.e. it was 4.3 times higher than in mineral soils. In the separated soil groups of organic origin, the average SOC content was in the range of 1.35–18.77%. Within these soil groups there was a small (CV = 18.4%) and medium variation in the SOC results (CV within 26.1–32.5%).

In the spatial system, the highest SOC content was found in soils of organic origin in the Podlaskie Voivodeship (14.67%), and the lowest in the Greater Poland Voivodeship (2.77%) – Table 7.

Table 6. Organic carbon content in the 0–30 cm layer of organic grassland soils in Poland

Type of soil[1)]	Organic matter content in a layer of 0–30 cm (%)	Number of samples	SOC content average	min	max	Standard deviation
			%			
Fully mineralised peat-muck	≤3	4	1.35	0.81	1.62	0.38
Mucky	(3–10⟩	47	4.00	1.77	5.74	1.05
Marsh	(10–20⟩	52	8.23	5.97	11.50	1.52
Mineral-muck	>20	54	18.77	11.72	43.27	6.10
Total organic		**157**	**10.42**	**0.81**	**43.27**	**7.35**

[1)] Soil types of organic origin were distinguished on the basis of Okruszko [1988], with partial use of soil nomenclature given by Pieściński and Gotkiewicz [1993].
Source: own study based on the results of National Chemical-Agricultural Station.

Table 7. Organic carbon content in the 0–30 cm layer of grassland soil of organic origin, depending on the voivodeship

Voivodeship	Number of samples	SOC content average	min	max	Standard deviation
		%			
Kuyavian-Pomeranian	11	8.54	3.85	22.81	5.62
Lublin	4	8.31	1.60	25.29	11.35
Lubusz	9	5.69	1.77	13.74	3.93
Łódź	9	10.53	0.81	43.27	13.31
Lesser Poland	1	6.96	6.96	6.96	0.00
Masovian	19	12.09	3.55	26.00	7.45
Podlaskie	37	14.67	4.80	24.64	5.87
Pomeranian	18	7.68	2.64	20.26	4.16
Silesian	1	5.74	5.74	5.74	0.00
Warmian-Masurian	31	11.25	2.68	41.30	7.71
Greater Poland	9	2.77	1.36	4.81	1.06
West Pomeranian	8	8.13	3.41	15.26	3.95
Poland	**157**	**10.42**	**0.81**	**43.27**	**7.35**

Source: own study based on the results of National Chemical-Agricultural Station.

Differentiation of SOC results analysed on a voivodeship scale, except for one case (Greater Poland Voivodeship), was large or very large.

When assessing the content of organic carbon (SOC) in the soils of grasslands according to the criteria developed by IUNG – PIB, it was found that almost 84% of mineral soils and nearly 100% of GL soils of organic origin in Poland are characterised by high and very high content of organic carbon – Table 8. Low SOC content is found in only 1% of mineral soils, and soils of organic

Table 8. Assessment of organic carbon (SOC) content in grassland soils (GL)

Content class	The percentage of GL soils in the SOC content classes			
	acc. to the IUNG – PIB classification		acc. to the EDS classification	
	types of soil			
	mineral	of organic origin	mineral	of organic origin
Very low	–	–	10.1	0.6
Low	1.0	0.0	38.7	3.2
Average	15.4	0.6	47.1	29.3
High	34.4	3.2	4.1	66.9
Very high	49.2	96.2	–	–
Total	**100.0**	**100.0**	**100.0**	**100.0**

Source: own study.

origin are not in this class. The rest of the soils are in the medium SOC content class. In the light of the criteria specified in the EDS, only in slightly more than 4% of mineral soils of GL in Poland the SOC content is high, while in more than 47% it is average, and in approx. 50% very low or low. In the case of soils of organic origin in nearly 67% of them content of SOC is high, in more than 29% medium, and in about 4% low and very low. According to EDS standards, very high content of SOC in GL soils in Poland (both mineral and organic origin) does not occur.

ORGANIC CARBON RESOURCES IN GRASSLAND SOILS

In Poland, the total area of grassland is 3,008,301 ha [GUS 2020]. It is assumed that GL located on soils of organic origin covers an area of 816,800 ha [Czaplak, Dembek 2000], although this area was established at the end of the 1990s. In 2000, the total acreage of GL was 3,872,100 ha [GUS 2009]. From then until 2020, it decreased by 22.3%. Assuming that a similar indicator showed the loss of GL located on soils of organic origin, it can be assumed that their current area is 634,585.9 ha. Hence, the area of mineral soils of grasslands is 2,373,715.1 ha (the difference between the total GL area of arable lands and the area of GL soils of organic origin). Taking into account the values of the volumetric density of mineral soils depending on their agronomic category (Tab. 3) and the shares of these soils in the studied set of mineral soils, it was established that the weighted average density of mineral soils GL was 1.46 $kg \cdot dm^{-3}$. On the other hand, on the basis of the determined average content of organic matter in the soils of GL of organic origin, which is at the level of 18.0%, it was calculated (Eq. 2) that the average density of soils of GL of organic origin is 0.80 $kg \cdot dm^{-3}$. Based on the above data and using the Polish average values of organic carbon content in mineral soils and grasslands of organic origin (Tabs. 4, 6), it was estimated (Eq. 1) that in the soil of grasslands in Poland – in their 0–30 cm layer – 412.7 Tg of SOC are contained (Tab. 9). More than 61% of these resources are contained in mineral soils, and approx. 39% in soils of organic origin.

Table 9. Organic carbon resources in the soils of grasslands (GL) in Poland in the 0–30 cm layer

Type of GL soils	SOC average resources ($Mg \cdot ha^{-1}$)	SOC resources (Tg)
Mineral	106.7	253.3
Of organic origin	251.2	159.4
GL total	**137.2**	**412.7**

Source: own study.

DISCUSSION

The mean content of organic carbon (SOC) in the mineral soils of Polish grasslands, determined on the basis of the conducted research, was 2.2 times higher than the average amount of SOC in the 0–20 cm layer of arable land, which in 1995–2015 was at the level of 1.12% (from 1.09 to 1.14%).

The highest SOC content in GL mineral soils was recorded in Podlaskie Voivodeship, which is the most developed in Poland in terms of milk production. It was found that there are directly proportional positive relationships between the SOC state of soil accumulation, at the NUTS 2 level[1] , and the number of cows and cattle per 100 ha of agricultural land (Fig. 2), and that they are statistically significant (r-Pearson coefficients between variables were 0.578 and 0.611, respectively; $p < 0.05$). Correlation relationships between the factors mentioned correspond to the findings of Hewins *et al.* [2018], which shows that on a regional scale, long-term grazing of livestock of moderate intensity may increase the SOC content in the 0–30 layer of mineral soil. Animal grazing results in an increased flow of organic matter to the soil in the form of faeces, thus increasing the activity of microorganisms present in it, which may favour SOC sequestration as a result of the formation of microbiological products [Gilmullina *et al.* 2020].

Among the distinguished categories of GL mineral soils, the SOC content was higher in very light soils (loose, slightly loamy sands) and light (loamy sands) than in medium soils (sandy and light loams), as well as heavy soils (medium and heavy loams, loams) – Table 4. However, the differences in organic carbon content between particular types of soil – as shown by the results of the Kruskal–Wallis test – were not statistically significant (Tab. 10). It should also be noted that the obtained data on the level of SOC in various soil categories do not coincide with the existing knowledge, that grassland soils rich in clay and dusty fractions generally have a higher SOM content than sandy soils [Loveland, Webb 2003; Rumpel 2011], or that fine-grained soils usually have a greater ability to retain SOC, and therefore contain more SOC than coarse-grained soils [Ding *et al.* 2014].

The results of organic carbon determinations in GL soils, classified according to the criteria developed by IUNG – PIB, differ significantly from the data relating to the general assessment of SOC in agricultural land in Poland. According to this assessment, soils with low organic carbon content constitute 6.2% of the AL area, medium – about 49.8%, and high and very

[1] NUTS = Nomenclature of Territorial Units for Statistics (Pol. Klasyfikacja Jednostek Terytorialnych do Celów Statystycznych); „2" = regions (or their parts).

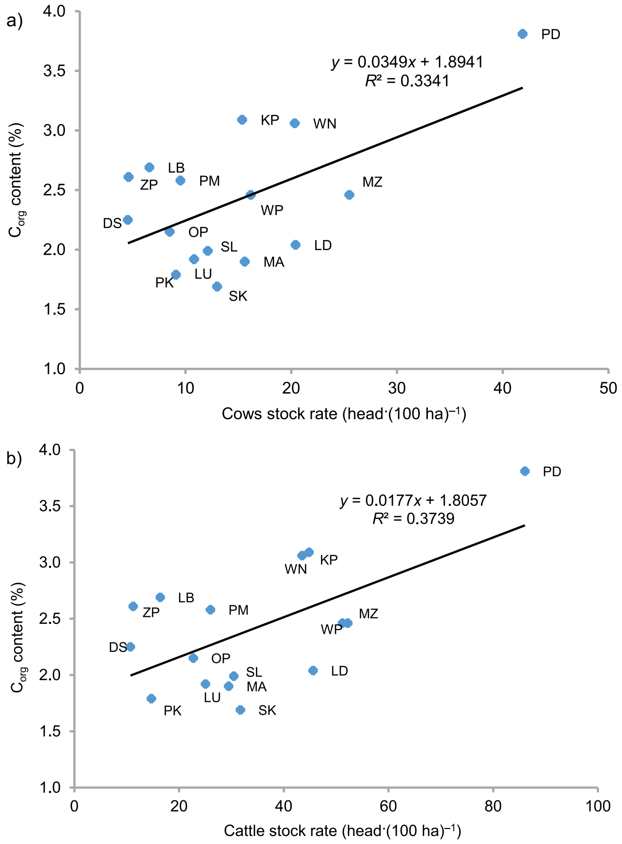

Fig. 2. The relationship between the livestock density per 100 ha of arable land and the content of organic carbon in mineral soils of grasslands: a) cows, b) cattle; codes for voivodeships in Poland (based on: ISO 3166-2: PL, 2): DS = Lower Silesia, KP = Kuyavian-Pomeranian, LU = Lublin, LB = Lubusz, LD = Łódź, MA = Lesser Poland, MZ = Masovian, OP = Opole, PK = Subcarpathian, PD = Podlaskie, PM = Pomeranian, SL = Silesian, SK = Świętokrzyskie, WN = Warmian-Masurian, WP = Greater Poland, ZP = West Pomeranian; source: own study

Table 10. Levels of significance of comparisons of the variable "organic carbon content (SOC)" between groups distinguished according to the category of mineral soils

Agronomic category of soils	*p*-value for multiple comparisons (two-tailed) [independent (grouping) variable: "soil category"; Kruskal–Wallis test: *H* (3, *N* = 703) = 3.706266; *p* = 0.2950]			
	VL R: 354.15	L R: 360.34	M R: 332.25	H R: 376.30
VL	–	1.0000	1.0000	1.0000
L	1.0000	–	0.9825	1.0000
M	1.0000	0.9825	–	0.4884
H	1.0000	1.0000	0.4884	–

Explanations: VL, L, M, H = categories as in Tab. 3, *N* = number of valid results, *H* = value of the Kruskal–Wallis test, *p* – level of statistical significance, *R* – average rank.
Source: own study.

high SOC – 33.4% and 10.6%, respectively [Jończyk *et al.* 2008]. It should be mentioned that it is commonly accepted that the content of 2% of organic carbon in soil is its critical value, below which soil quality may potentially decrease [Loveland, Webb 2003; Montanarella, Panagos 2015; Musinguzi *et al.* 2013]. In the context of the above, it can be concluded that about 49% of mineral soils of GL require an increase in the organic matter content. In the case of soils of organic origin, almost 67% of them, according to the EDS criteria, have a high SOC content, over 29% – average, and approx. 4% belong to classes with the poorest content of this component. These soils are particularly susceptible to the loss of organic matter. It was found that in the climatic conditions of Poland, peat soils used as meadows and pastures after drainage settle on average within 1 cm per year and lose 7–15 Mg OM·ha^{-1}·y^{-1} [Lipiński 2006; Piaścik, Gotkiewicz 2004]. The basic condition for limiting SOC losses from GL soils of organic origin is good moistening of their root layer. This requires the maintenance of a groundwater level adjusted to the type of habitat by means of a permanent subsoil irrigation system [Jurczuk 2004; 2009].

In the soils of Polish grasslands, taking into account their top 30 cm layer, according to the estimates carried out, about 413 Tg of SOC are stored. This value is lower than that given by Kuś [2015], who determined that 445 Tg of SOC are contained in the level of 0–30 cm of GL soils, including 205 Tg in mineral soils and 240 Tg in soil of organic origin. In his calculations (made using a different method), this author assumed the area of GL from 2014 amounting to approximately 3.1 mln ha, including the area of soils of organic origin – 0.8 mln ha. Per one hectare of area, over 137 Mg of SOC is deposited in the upper zone of 0–30 cm of grassland soil in Poland. On the other hand, in GL soils of the same thickness in Japan, an accumulation of organic carbon in an average amount of 114 Mg·ha^{-1} was recorded [Matsuura *et al.* 2012], and in the profile to a depth of 1 m of Belgian GL soils from the Flamandia region, the presence of SOC was found at an average level of 143 Mg·ha^{-1} [Mestdagh *et al.* 2009]. This indicates that, in comparison with interchangeable countries, the unit SOC resources of Polish GL are relatively large.

Possibilities of carbon sequestration in meadow soils in Poland are much greater than the level of its estimated resources, which was determined with the reservation mentioned in the introduction that approx. 50% of GL is degraded. The potential in this respect is to some extent well illustrated by the results of calculations showing that in mineral soils of GL covering half of their area, an increase in organic carbon resources by 51.9 Tg can be obtained, if the level of SOC content in these soils was increased by 1%.

Regarding the degradation of grasslands, it should be emphasised that it occurs as a result of changes in the conditions of growth and development of grasslands caused by factors: edaphic (including chemical, physical and biological properties of the soil), climatic and anthropogenic [Baryła, Kulik 2011]. Among these factors, edaphic factors, such as soil acidification and nutrient sterilisation, have an important impact on the degradation of grasslands in Poland. This is indicated by the research of Pietrzak *et al.* [2019], which shows that the soils of grasslands in Poland are characterised by:
- a largely unfavourable reaction (about 41% of grassland soils are very acidic or acidic; the optimum reaction is 30.3% of soils);
- serious deficiencies of available forms of phosphorus (the share of GL soils with very low and low P abundance is over 59%; the

classes with the highest abundance, i.e. "high" and "very high", include slightly more than 30% of soils);

– very large deficiencies of assimilable forms of potassium (about 78% of GL soils are "low" or "very low" rich in potassium, including 97% of organic soils of GL; soils in the "high" and "very high" fertility classes are only 13.2%).

Anthropogenic factors, in particular those related to the regulation of water conditions in their soil environment, also exert a great influence on the degradation of grasslands. The problem of proper moistening of meadow soils is very important, considering that approx. 70% of GL in Poland is located in areas with a water deficit [Bagiński *et al.* 2020]. Meanwhile, on the drained grasslands, which cover an area of 1776.9 thous. ha [GUS 2017], the technical and functional condition of melioration devices is unsatisfactory. It is estimated that 70% of these devices are not maintained in technical efficiency (i.e. they are not maintained, mown, desludged, repaired), and more than 32% of those maintained require urgent renovations and repairs [Kłos 2013]. In addition, grassland drainage needs are currently not sufficiently met. According to Nyc and Pokładek [2008], these needs concern 2,186.9 thous. ha GL.

With regard to the discussed factors of grassland degradation, it should be emphasised that studies conducted by various authors prove that there is a positive relationship between the SOC content in grassland soils and their pH [Karabcová *et al.* 2015], the state of humidity [Kerr, Ochsner 2020; Tian *et al.* 2016], and the level of fertilisation [Vargová *et al.* 2020].

In the context of the above, it can be concluded that an increase in the level of organic carbon sequestration in the soils of grasslands in Poland can be achieved by renewing their degraded part, in particular by actions aimed at optimising the reaction (through liming), fertility (through balanced fertilisation) and soil moisture (through efficient and adequate drainage systems). Under specific conditions, these activities should be differentiated depending on the factors responsible for the degradation of grassland and its degree. In some areas of GL, it will be sufficient for their renovation to rationalise fertilisation and regulate the pH of the soil, for others to enrich the sward with valuable plant species using the undersowing method, and in others – to use full cultivation [Barszczewski *et al.* 2015], each time in connection with ensuring the proper condition of water conditions in the soil environment, as well as with the use of other justified measures. Renovation of the full cultivation by plowing method is beneficial due to the yield and quality of fodder from grasslands, however, it carries the risk of losing organic carbon from their soil resources in the first period after application [Kayser *et al.* 2018], therefore it should be used when necessary.

The discussed results of research on the quantitative state of SOC in the soils of grasslands in Poland and the methods of increasing this state recommended against them, contribute to the international initiative "4 per 1000". Its aim is to show that agriculture, and agricultural land in particular, can play a key role in food security and climate change. It serves, inter alia, as an international multidisciplinary platform to communicate with the scientific community and various stakeholders in promoting remedial measures to increase SOC sequestration [Rumpel *et al.* 2019]. Within this initiative, the currently preferred solution is to increase the carbon flows into the soil through management practices adapted to local conditions [Dignac *et al.* 2017].

CONCLUSIONS

The conducted research allowed for a comprehensive diagnosis of the content and abundance of organic carbon in the soils of grasslands in Poland in a spatial arrangement, as well as for a multi-faceted analysis of this state. In particular, they showed that the average SOC content in the 0–30 cm layer of mineral soils of grasslands in Poland is 2.44%, and that of organic soils – 10.42%, while in this layer, a total of 412.7 Tg of SOC are stored (253.3 Tg in mineral soils and 159.4 Tg in soils of organic origin). When assessing the obtained research results on the basis of the criteria of the European Soil Bureau, it was found that about 49% of GL mineral soils are characterised by a very low or low SOC content. Therefore, and on the basis of the existing knowledge that over 50% of grasslands in Poland are degraded, it was indicated that there are great opportunities to increase the sequestration of organic carbon in their soils. It was decided that the possibility of increasing the SOC resources in Polish GL soils can be achieved by improving their pH, nutrient content and moisture level. It has also been shown independently that the accumulation of SOC in GL soils is positively influenced by an increase in the density of cattle, including cows, in a given area.

In a practical sense, the results of the research work carried out and the recommendations resulting from them can be used to develop a strategy in Poland to increase the sequestration of organic carbon in agricultural land soils in the aspect of counteracting climate warming. The results of these works constitute a case study specific for Central European conditions, which should be treated as an element of the international initiative "4 per 1000".

ACKNOWLEDGMENTS

The Authors would like to express their gratitude to the National Chemical and Agricultural Station for the possibility of using the results of field and laboratory tests.

REFERENCES

Bagiński L., Balcerowicz M., Baryła A., Bus A., Herbich P., Kaca E., …, Żelazo J. 2020. Analiza kształtowania i wykorzystania zasobów wodnych dla celów rolnictwa i obszarów wiejskich [Analysis of the formation and use of water resources for agriculture and rural areas]. Warszawa. Forum Inicjatyw Rozwojowych. ISBN 978-83-955139-1-6 pp. 142.

Barszczewski J., Jankowska-Huflejt H., Mendra M. 2015. Renowacja trwałych użytków zielonych [Renovation of permanent grassland]. Falenty. Wydawnictwo ITP. Materiały Informacyjne. Nr 42. ISSN 08060-1410 pp. 20.

Baryła R., Kulik M. 2011. Podsiew zdegradowanych zbiorowisk trawiastych metodą ich regeneracji przyjazną środowisku [Sowing of degraded grasslands with an environmentally friendly method of regeneration]. Zeszyty Naukowe WSA w Łomży. Z. 47 p. 7–17.

Batjes N.H. 1999. Management options for reducing CO_2-concentrations in the atmosphere by increasing carbon sequestration in the soil. Report 410-200-031. Dutch National Research Programme on Global Air Pollution and Climate Change & Technical Paper 30. Wageningen. International Soil Reference and Information Centre pp. 126.

Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system. COM(2020) 381 final [online]. [Access 15.08.2021]. Available at: https://eur-lex.europa.eu/resource.html?uri=cellar:ea0f9f73-9ab2-11ea-9d2d-01aa75ed71a1.0001.02/DOC_1&format=PDF

Conant R.T. 2010. Challenges and opportunities for carbon sequestration in grassland systems. A technical report on grassland management and climate mitigation. Ed. R.T. Conant. Integrated Crop Management 9-2010. Rome. FAO. ISBN 978-92-5-106494-8 pp. 67.

Conant R., Paustian K., Elliott E. 2001. Grassland management and conversion into grassland: Effects on soil carbon. Ecological Applications. Vol. 11(2) p. 343–355. DOI 10.2307/3060893.

Conant R.T., Cerri C.E.P., Osborne B.B., Paustian K. 2017. Grassland management impacts on soil carbon stocks: a new synthesis. Ecological Applications. Vol. 27(2) p. 662–668. DOI 10.1002/eap.1473.

Crème A., Rumpel C., Malone S.L., Saby N.P.A., Vaudour E., Decau M. L., Chabbi A. 2012. Monitoring grassland management effects on soil organic carbon – A matter of scale. Agronomy. Vol. 10(12), 2016. DOI 10.3390/agronomy10122016.

Czaplak I., Dembek W. 2000. Torfowiska Polski jako źródło emisji dwutlenku węgla [Polish peatlands as a source of carbon dioxide emissions]. Zeszyty Edukacyjne. Rolnictwo Polskie i Ochrona Jakości Wody. Z. 6 p. 61–71.

Dignac M.F., Derrien D., Barré P., Barot S., Cécillon L., Chenu C., …, Basile-Doelsch I. 2017. Increasing soil carbon storage: mechanisms, effects of agricultural practices and proxies. A review. Agronomy for Sustainable Development. Vol. 37, 14. DOI 10.1007/s13593-017-0421-2.

Ding F., Huang Y., Sun W., Jiang G., Chen Y. 2014. Decomposition of organic carbon in fine soil particles is likely more sensitive to warming than in coarse particles: An incubation study with temperate grassland and forest soils in Northern China. PLOS One. Vol. 9(4), e95348. DOI 10.1371/journal.pone.0095348.

Epple C., García Rangel S., Jenkins M., Guth M. 2016. Managing ecosystems in the context of climate change mitigation: A review of current knowledge and recommendations to support ecosystem-based mitigation actions that look beyond terrestrial forests. Technical Series. No. 86. Montreal. Secretariat of the Convention on Biological Diversity. ISBN 978929225646 pp. 55.

Fajer M. 2014. Przewodnik do ćwiczeń z gleboznawstwa dla studentów I roku geografii [A guide to soil science exercises for first-year geography students]. Katowice. Wydawnictwo UŚ. ISBN 978-83-226-2260-5 pp. 134.

Fotyma M., Kęsik K., Pietruch C. 2010. Azot mineralny w glebach jako wskaźnik potrzeb nawozowych roślin i stanu czystości wód glebowo-gruntowych [Mineral nitrogen in soils as an indicator of the fertilization needs of plants and the cleanliness of soil and groundwater]. Nawozy i Nawożenie. Nr 38 p. 5–80.

Gilmullina A., Rumpel C., Blagodatskaya E., Chabbi A. 2020. Management of grasslands by mowing versus grazing – Impacts on soil organic matter quality and microbial functioning. Applied Soil Ecology. Vol. 156, 103701. DOI 10.1016/j.apsoil.2020.103701.

Godde C.M., de Boer I.J.M., Ermgassen E., Herrero M., van Middelaar C.E., Muller A., …, Garnett T. 2020. Soil carbon sequestration in grazing systems: Managing expectations. Climatic Change. Vol. 161(3) p. 385–391. DOI 10.1007/s10584-020-02673-x.

GUS 2009. Użytkowanie gruntów, powierzchnia zasiewów i pogłowie zwierząt gospodarskich w 2009 r. [Land use, sown area and livestock population in 2009]. Warszawa. Główny Urząd Statystyczny. ISSN 1507-9600 pp. 183.

GUS 2017. Rocznik statystyczny rolnictwa 2017 [Statistical yearbook of agriculture 2017]. Warszawa. Główny Urząd Statystyczny. ISSN 2080-8798 pp. 495.

GUS 2020. Użytkowanie gruntów i powierzchnia zasiewów w 2019 roku [Land use and sown area in 2019] [online]. Warszawa. Główny Urząd Statystyczny. ISSN 2353-5180. [Access 15.08.2021]. Available at: https://stat.gov.pl/obszary-tematyczne/rolnictwo-lesnictwo/rolnictwo/uzytkowanie-gruntow-i-powierzchnia-zasiewow-w-2019-roku,8,15.html

Hewins D.B., Lyseng M.P., Schoderbek D.F., Alexander M., Willms W. D., Carlyle C.N., Chang S.X., Bork E.W. 2018. Grazing and climate effects on soil organic carbon concentration and particle-size association in northern grasslands. Scientific Reports. Vol. 8, 1336. DOI 10.1038/s41598-018-19785-1.

IUNG 1983. Metody badań laboratoryjnych w stacjach chemiczno-rolniczych. Cz. IV. Badania gleb, ziem i podłoży spod warzyw i kwiatów oraz części wskaźnikowych roślin w celach diagnostycznych [Laboratory test methods in chemical and agricultural stations. Part IV. Research of soils, ground and substrates under vegetables and flowers as well as indicator parts of plants for diagnostic purposes]. Puławy. Instytut Uprawy Nawożenia i Gleboznawstwa pp. 87.

Jiang Y., Zhang D., Ostle N., Luo C., Wang Y., Ding P., Cheng Z., Shen C., Zhang, G. 2021. Flexible soil microbial carbon metabolism across an Asian elevation gradient. Radiocarbon. Vol. 63(5) p. 1397–1413. DOI 10.1017/RDC.2021.57.

Jones M.B. 2010. Potential for carbon sequestration in temperate grassland soils. In: Grassland carbon sequestration: Management, policy and economics. Eds. M. Abberton, R. Conant, C. Batello. Proceedings of the Workshop on the role of grassland carbon sequestration in the mitigation of climate change. Integrated Crop Management 11-2010. Rome. FAO p. 1–18.

Jończyk K., Jadczyszyn J., Filipiak K., Stuczyński T. 2008. Przestrzenne zróżnicowanie zawartości materii organicznej w glebach Polski w kontekście ochrony gleb i ich rolniczego wykorzystania [Spatial differentiation of organic matter content in Polish soils in the context of soil protection and their agricultural use]. Studia i Raporty IUNG – PIB. Vol. 12 p. 133–142.

Jurczuk S. 2004. Warunki wodne ograniczające straty masy organicznej na łąkach o glebach torfowo-murszowych [Water conditions limiting the loss of organic matter in meadows with peat-muck soils]. Woda-Środowisko-Obszary Wiejskie. T. 4. Z. 2a(11) p. 379–394.

Jurczuk S. 2009. Możliwości rolniczego gospodarowania na użytkach zielonych w warunkach ograniczenia degradacji gleb torfowo-murszowych [Possibilities of agricultural farming on grasslands in conditions of limiting the degradation of peat-muck soils]. Woda-Środowisko-Obszary Wiejskie. T. 9. Z. 3(27) p. 57–75.

Karabcová H., Pospíšilová L., Fiala K., Škarpa P., Bjelková M. 2015. Effect of organic fertilizers on soil organic carbon and risk trace elements content in soil under permanent grassland. Soil and Water Research. Vol. 10 p. 228–235. DOI 10.17221/5/2015-SWR.

Kayser M., Müller J., Isselstein J. 2018. Grassland renovation has important consequences for C and N cycling and losses. Food and Energy Security. Vol. 7(4), e00146. DOI 10.1002/fes3.146.

Kerr D.D., Ochsner T.E. 2020. Soil organic carbon more strongly related to soil moisture than soil temperature in temperate grasslands. Soil Science Society of America Journal. Vol. 84 p. 587–596. DOI 10.1002/saj2.20018.

Kłos L. 2013. Stan i funkcjonowanie urządzeń melioracji wodnych na obszarach wiejskich [Condition and functioning of water drainage facilities in rural areas]. Ekonomia i Środowisko. Vol. 3 (46) p. 196–206.

Kuś J. 2015. Glebowa materia organiczna – znaczenie, zawartość i bilansowanie [Soil organic matter – importance, content and balancing]. Studia i Raporty IUNG – PIB. Vol. 45(19) p. 27–53.

Lipiński J. 2006. Zarys rozwoju oraz produkcyjne i środowiskowe znaczenie melioracji w świetle badań [Outline of development as well as production and environmental importance of melioration in the light of research]. Acta Scientiarum Polonorum Formatio Circumiectus. Vol. 5(1) p. 3–15.

Lorenz K., Lal R. 2018. Carbon sequestration in grassland soils. In: Carbon sequestration in agricultural ecosystems. Eds. K. Lorenz, R. Lal. Cham. Springer p. 175–209.

Louis B.P., Maron P.A., Viaud V., Leterme P., Menasseri-Aubry S. 2016. Soil C and N models that integrate microbial diversity. Environmental Chemistry Letters. Vol. 14 p. 331–344. DOI 10.1007/s10311-016-0571-5.

Loveland P., Webb J. 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: A review. Soil & Tillage Research. Vol. 70(1) p. 1–18. DOI 10.1016/S0167-1987(02)00139-3.

Łądkiewicz K., Wszędyrówny-Nast M., Jaśkiewicz K. 2017. Porównanie różnych metod oznaczania zawartości substancji organicznej [Comparison of different methods for determining the content of organic matter]. Przegląd Naukowy – Inżynieria i Kształtowanie Środowiska. T. 26. Z. 1 p. 99–107. DOI 10.22630/PNIKS.2017.26.1.09.

Matsuura S., Sasaki H., Kohyama K. 2012. Organic carbon stocks in grassland soils and their spatial distribution in Japan. Grassland Science. Vol. 58(2) p. 79–93. DOI 10.1111/j.1744-697X.2012.00245.x.

McGonigle T.P., Turner W.G. 2017. Grasslands and croplands have different microbial biomass carbon levels per unit of soil organic carbon. Agriculture. Vol. 7(7), 57. DOI 10.3390/agriculture7070057.

Mestdagh I., Sleutel S., Lootens P., Van Cleemput O., Beheydt D., Boeckx P. , …, Carlier L. 2009. Soil organic carbon-stock changes in Flemish grassland soils from 1990 to 2000. Journal of Plant Nutrition and Soil Science. Vol. 172 p. 24–31. DOI 10.1002/jpln.200700132.

Montanarella L., Panagos P. 2015. Policy relevance of critical zone science. Land Use Policy. Vol. 49 p. 86–91. DOI 10.1016/j.landusepol.2015.07.019.

Musinguzi P., Tenywa J.S., Ebanyat P., Tenywa M.M., Mubiru D.N., Basamba T.A., Leip A. 2013. Soil organic carbon thresholds and nitrogen management in tropical agroecosystems: concepts and prospects. Journal of Sustainable Development. Vol. 6(12) p. 31–43. DOI 10.5539/jsd.v6n12p31.

Nawalany P. 2021. Unpublished material. Personal communicaton.

Nyc K., Pokładek R. 2008. Aktualne problemy melioracji użytków zielonych [Current problems of grassland melioration]. Woda-Środowisko-Obszary Wiejskie. T. 8. Z. 2b(24) p. 97–103.

Okruszko H. 1988. Zasady podziału gleb hydrogenicznych na rodzaje oraz łączenia rodzajów w kompleksy [Principles of dividing hydrogenic soils into types and combining types into complexes]. Roczniki Gleboznawcze. T. 39. Z. 1 p. 127–152.

O'Mara F.P. 2012. The role of grasslands in food security and climate change. Annals of Botany. Vol. 110(6) p. 1263–1270. DOI 10.1093/aob/mcs209.

Paulsen H.M. 2020. Introduction: Carbon sequestration in agricultural soils. In: Inventory of techniques for carbon sequestration in agricultural soils. Ed. H.M. Paulsen. 's-Hertogenbosch. Interreg North Sea Region p. 3–5.

Piaścik H., Gotkiewicz J. 2004. Przeobrażenia odwodnionych gleb torfowych jako przyczyna ich degradacji [Transformations of drained peat soils as the cause of their degradation]. Roczniki Gleboznawcze. T. 55. Z. 2 p. 331–338.

Pieściński J., Gotkiewicz J. 1993. Gleby organiczne i mineralno-organiczne sandru mazursko-kurpiowskiego [Organic and mineral-organic soils of Masurian-Kurpie outwash plain]. Zeszyty Naukowe Ostrołęckiego Towarzystwa Naukowego. Z. 7 p. 254–262.

Pietrzak S. 2012a. Azotany w wodach gruntowych na terenach zajmowanych przez użytki zielone w Polsce [Nitrates in groundwater in areas occupied by grasslands in Poland]. Polish Journal of Agronomy. Vol. 11 p. 34–40.

Pietrzak S. 2012b. Odczyn i zasobność gleb łąkowych w Polsce [Reaction and abundance of meadow soils in Poland]. Woda-Środowisko-Obszary Wiejskie. T. 12. Z. 1(37) p. 105–117.

Pietrzak S. 2015. Kształtowanie się stanu ilościowego azotu mineralnego w glebach organicznych pod użytkami zielonymi w Polsce [Formation of the quantitative state of mineral nitrogen in organic soils under grasslands in Poland]. Woda-Środowisko-Obszary Wiejskie. T. 15. Z. 2(50) p. 87–96.

Pietrzak S., Juszkowska D., Nawalany P. 2019. Zmiany odczynu i zasobności gleb użytków zielonych w Polsce między 2008 a 2016 rokiem [Changes in the reaction and fertility of soils in grasslands in Poland between 2008 and 2016]. Zagadnienia Doradztwa Rolniczego. Nr 1 p. 50–71.

Pikuła D. 2015. Aspekty środowiskowe gospodarowania materią organiczną w rolnictwie [Environmental aspects of managing organic matter in agriculture]. Economic and Regional Studies. Vol. 8(2) p. 98–112.

Rumpel C. 2011. Carbon storage and organic matter dynamics in grassland soils. In: Grassland productivity and ecosystem services. Eds. G. Lemaire, J. Hodgson, A. Chabbi. Wallingford, Cambridge. CAB International p. 65–72.

Rumpel C., Amiraslani F., Chenu C., Garcia Cardenas M., Kaonga M., Koutika L.S., …, Wollenberg E. 2019. The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. Ambio. Vol. 49. Iss. 1 p. 350–360. DOI 10.1007/s13280-019-01165-2.

Sapek B. 2009. Zapobieganie stratom i sekwestracja węgla organicznego w glebach łąkowych [Loss prevention and organic carbon sequestration in meadow soils]. Inżynieria Ekologiczna. Nr 21 p. 48–61.

Tessema B., Sommer R., Piikki K., Soderstrom M., Namirembe S., Notenbaert A., Tamene L., Nyawira S., Paul B. 2020. Potential for soil organic carbon sequestration in grasslands in East African countries: A review. Grassland Science. Vol. 66 p. 135–144. DOI 10.1111/grs.12267.

Tian F.P., Zhang Z.N., Chang X.F., Sun L., Wei X.H., Wu G.L. 2016. Effects of biotic and abiotic factors on soil organic carbon in semi-arid grassland. Journal of Soil Science and Plant Nutrition. Vol. 16(4) p. 1087–1096. DOI 10.4067/S0718-95162016005000080.

Vargová V., Kanianska R., Kizeková M., Šiška B., Kováčiková Z., Michalec M. 2020. Changes and interactions between grassland ecosystem soil and plant properties under long-term mineral fertilization. Agronomy. Vol. 10(3), 375. DOI 10.3390/agronomy10030375.

Whitehead D. 2020. Management of grazed landscapes to increase soil carbon stocks in temperate, dryland grasslands. Frontiers in Sustainable Food Systems. Vol. 4, 585913. DOI 10.3389/fsufs.2020.585913.

Yu P., Liu S., Ding Z., Zhang A., Tang X. 2020. Changes in storage and the stratification ratio of soil organic carbon under different vegetation types in Northeastern China. Agronomy. Vol. 10(2), 290. DOI 10.3390/agronomy10020290.