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Research Article

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Abstract
The aim of the study is to evaluate the content of organic carbon ($C_{org}$) in the soils of Polish grasslands (GL). The Tiurin’s method (mineral soils) and the mass loss method (soil of organic origin) were used. It was found that: /i/ the average $C_{org}$ content of mineral soils is 2.44% and of organic soils – 10.42%; /ii/ according to the Polish criteria, about 84% of GL mineral soils are classified as classes with high and very high $C_{org}$ content, and over 15% and 1% – in classes with medium and low $C_{org}$ content, respectively; more than 99% of organic soils belong to two classes with the highest $C_{org}$ 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 $C_{org}$ 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 million tons of $C_{org}$. There are opportunities to increase the $C_{org}$ stock in meadow soils.

Keywords: grassland, mineral soils, soils of organic origin, organic matter, organic carbon

INTRODUCTION
Grassland soils are characterized 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 [1]. The reserves of organic matter in permanent grassland soils are usually much greater than in cultivated soils. 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 [2]. The formation of large amounts of organic matter in GL soils is favored by their permanent plant cover, due to the fact that it is characterized 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) [3]. Looking from a different point of view, the greater accumulation of organic matter in GL soils as compared to arable land is favored 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 accumulate in the soils of grasslands [4]. 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 [5–9]. It is estimated that up to 30% of the world's SOC resources are 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 [10]. The soils of degraded grasslands have a very high potential for carbon sequestration (i.e. removing CO₂ from the atmosphere and storing it in the soil via meadow sward) [11]. Possibilities of using this potential are created, in particular, by activities aimed at increasing yields from GLs through the use of fertilizers 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 minimizing the negative effects of grazing [12–14].

Permanent GLs in Poland cover over 3.1 million ha, i.e. 21.3% of the agricultural land area [15]. 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) [16]. 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 [17].

The problem of storing and shaping organic carbon in the soils of grasslands in Poland is not sufficiently recognized in quantitative terms. Given the importance of grassland in mitigating climate change and the practical challenges it poses it needs further investigation. This work fits within these needs. Its purpose is to determine the content and abundance of organic carbon in grassland soils in Poland.

**TEST MATERIAL AND METHODS**

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 (KSChR) and regional chemical and agricultural stations, in cooperation with the Institute of Technology and Life Sciences (ITP) [18, 19]. Soil samples for research were taken from a depth of 30 cm from 860 permanent monitoring points of grassland soils throughout Poland, of which 703 were located on mineral soils and 157 on organic soils – table 1. Soil material for laboratory analyzes was obtained mainly in 2008 and a small part in the next few years.
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 hours (weight loss during calcination was taken as the content of organic matter) [20]. 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 ($C_{org}$, %) in the tested samples was calculated by dividing the obtained OM value (%) by the van Bemmelen coefficient, amounting to 1.724 [21]. The organic carbon content was determined by the Tiurin's method in the samples of mineral soils. The Tiurin's 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’ [22]. 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$^{-1}$).

$C_{org}$ soil resources were calculated from the formula [8, 23, 24]:

$$Z_{C_{org}} = 0,01 \cdot C_{org} \cdot y \cdot h \cdot 10000 \quad (1)$$

where:

- $Z_{C_{org}}$ – organic carbon resources in the 0–30 soil layer, kg ∙ ha$^{-1}$;
- $C_{org}$ – organic carbon content in the 0–30 soil layer, %;
- $h$ – thickness of the soil layer, m;
- $y$ – soil volumetric density (volumetric weight), t ∙ m$^{-3}$;

The bulk density of mineral soils was adopted after Fotyma et al. [25] – table 3.

The density of organic soils was determined using the following equation [26]:

$$y = -0,000006 \cdot OM^3 + 0,001 \cdot OM^2 - 0,06235 \cdot OM + 1,6346 \quad (R^2 = 0,9489) \quad (2)$$

where:
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 \( C_{\text{org}} \) content in the soil and the cattle density in the voivodships was carried out;
- the significance of differences between the average \( C_{\text{org}} \) 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 Falenty on the basis of data provided by the KSChR.

**RESEARCH RESULTS**

**Organic carbon content in grassland soils**

In the analyzed research period, the average content of organic carbon (\( C_{\text{org}} \)) 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 \( C_{\text{org}} \) were found in light soils, and the lowest in medium soils.

[Table 4]

In individual voivodships, the average content of \( C_{\text{org}} \) in the mineral soils of UZ oscillated between 1.79% and 3.81%, wherein the populations of the results on the basis of which it was determined were characterized 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.

[Table 5]

In the case of organic soils of grasslands, the national average content of organic carbon in the 0–30 cm layer was 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 C$_{org}$ 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 C$_{org}$ results (CV within 26.1–32.5%).

[Table 6]

In the spatial system, the highest C$_{org}$ 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. Differentiation of C$_{org}$ results analyzed on a voivodeship scale, except for one case (Greater Poland voivodeship), was large or very large.

[Table 7]

When assessing the content of organic carbon (C$_{org}$) 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 characterized by high and very high content of organic carbon – table 8. Low C$_{org}$ content is found in only 1% of mineral soils, and soils of organic origin are not in this class. The rest of the soils are in the medium C$_{org}$ content class. In the light of the criteria specified in the European Database on Soils, only in slightly more than 4% of mineral soils of GL in Poland the C$_{org}$ content is high, while in more than 47% it is average, and in approx. 50% very low or low.

[Table 8]

Organic carbon resources in grassland soils

In Poland, the total area of grassland is 3,008,301 ha [15]. It is assumed that GL located on soils of organic origin covers an area of 816,800 ha [27], although this area was established at the end of the 1990s. In 2000, the total acreage of GL was 3,872,100 ha [28]. 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 – table 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 dm$^{-3}$ (t m$^{-3}$). 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 (equation 2) that the average density of soils of GL of organic origin is 0.80 kg dm$^{-3}$ (t m$^{-3}$). Based on the above data and using the Polish
average values of organic carbon content in mineral soils and grasslands of organic origin (tables 4 and 6), it was estimated (equation 1) that in the soil of grasslands in Poland – in their 0–30 cm layer – 412.7 million tonnes of C$_{org}$ are contained – table 9. More than 61% of these resources are contained in mineral soils, and approx. 39% in soils of organic origin.

[Table 9]

DISCUSSION OF RESEARCH RESULTS

The mean content of organic carbon (C$_{org}$) 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 C$_{org}$ in arable land, which is at the level of 1.12% (in 1995–2015, at a depth of up to 20 cm) [29] – table 10.

[Table 10]

The highest C$_{org}$ 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 C$_{org}$ state of soil accumulation, at the NUTS 2 level, and the number of cows and cattle per 100 ha of agricultural land – Fig. 1 and 2, and that they are statistically significant – Table 11. Correlation relationships between the factors mentioned correspond to the findings of Hewins et al. [30], which shows that on a regional scale, long-term grazing of livestock of moderate intensity may increase the C$_{org}$ content in the 0–30 layer of mineral soil.

[Fig. 1]

[Fig. 2]

[Table 11]

Among the distinguished categories of GL mineral soils, the C$_{org}$ 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 – table 12. It should also be noted that the obtained data on the level of C$_{org}$ 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 [31, 32], or that
fine-grained soils usually have a greater ability to retain SOC, and therefore contain more SOC than coarse-grained soils [33].

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 $C_{org}$ 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 high $C_{org} – 33.4\%$ and $10.6\%$, respectively [34]. 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 [31, 35, 36]. 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 $C_{org}$ 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 t OM · ha$^{-1}$ · year$^{-1}$ [37, 38]. The basic condition for limiting $C_{org}$ 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 – table 13 – by means of a permanent subsoil irrigation system [39].

In the soils of Polish grasslands, taking into account their top 30 cm layer, according to the estimates carried out, about 413 million tons of $C_{org}$ are stored. This value is lower than that given by Kuś [24], who determined that 445 million tons of $C_{org}$ are contained in the level of 0–30 cm of GL soils, including 205 million tons in mineral soils and 240 million tons 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 million ha, including the area of soils of organic origin – 0.8 million ha. The possibilities of carbon sequestration from 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 (million tonnes) can be obtained, if the level of $C_{org}$ content in these soils was increased by 1%.

Regarding the degradation of grasslands, it should be emphasized 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 [40]. Among these factors, edaphic factors, such as soil acidification and nutrient sterilization, have an important impact on the degradation of grasslands in Poland. This is indicated by the research of Pietrzak et al. [41], which shows that the soils of grasslands in Poland are characterized by:

- a largely unfavorable 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 K, 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 [42]. Meanwhile, on the drained grasslands, which cover an area of 1776.9 thousand. ha [43], 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 [44]. In addition, grassland drainage needs are currently not sufficiently met. According to Nyc and Pokładek [45], these needs concern 2,186.9 thous. ha GL.

With regard to the discussed factors of grassland degradation, it should be emphasized that studies conducted by various authors prove that there is a positive relationship between the $C_{org}$ content in grassland soils and their pH [46], the state of humidity [47, 48], and the level of fertilization [49].

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 optimizing the reaction (through liming), fertility (through balanced fertilization) 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 rationalize fertilization 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 [16], 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 [50], therefore it should be used when necessary.
The discussed results of research on the quantitative state of C\textsubscript{org} 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 [51]. Within this initiative, the currently preferred solution is to increase the carbon flows into the soil through management practices adapted to local conditions [52].

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 C\textsubscript{org} 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 million tonnes of C\textsubscript{org} are stored (253.3 million tonnes in mineral soils and 159.4 million tonnes 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 characterized by a very low or low C\textsubscript{org} 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 C\textsubscript{org} 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 C\textsubscript{org} 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’.

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DECLARATIONS

Authors’ contributions

S. Pietrzak: developing a research concept, conducting a literature review, compiling, analyzing and interpreting research results, preparing a manuscript of the article in Polish.

J.T. Holaj-Krzak: statistical analysis of research results, editing of the manuscript in Polish, translation and editing of the manuscript in English.

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**Fig. 1.** The relationship between the cows population per 100 ha of arable land and the content of organic carbon in mineral soils of grasslands. Explanation: codes for voivodships 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

**Fig. 2.** The relationship between the cattle stock per 100 ha of arable land and the content of organic carbon in mineral soils of grasslands; explanations as for fig. 1. Source: own study
Table 1. The number of monitoring points for grassland soils

| Type of soil | Poland | Łódź | Lesse Poland | Masovian | Opole | Subcarpathian | Podlaskie | Pomeranian | Silesian | Świętokrzyskie | Warmian-Masurian | Greater Poland | West Pomeranian |
|--------------|--------|------|--------------|----------|-------|--------------|-----------|------------|---------|---------------|-----------------|----------------|-----------------|
| Mineral      | 703    | 15   | 19           | 38       | 26    | 34           | 62        | 106        | 15      | 53            | 67              | 25             | 39              |
| Organic      | 157    | —    | 11           | 4        | 9     | 9            | 1         | 19         | —       | —             | 37              | 18             | 1               |
| Total        | 860    | 43   | 30           | 42       | 35    | 43           | 63        | 125        | 15      | 53            | 104             | 43             | 40              |

Source: own elaboration based on the KSChR results
Table 2. Criteria for assessing the content of organic carbon ($C_{org}$) in the soils of Poland and Europe [24, 53]

| Content class | Classification by IUNG-PIB | Classification by European Database on Soils, 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                                         | —                       | —                       |
Table 3. The bulk density of mineral soils depending on their agronomic category [25]

| Agronomic category of soils | The proportion of floating particles in diameter < 0.02 mm | Soil density kg · dm⁻³ (t · m⁻³) |
|----------------------------|--------------------------------------------------------|---------------------------------|
| Very light (VL)            | ≤ 10                                                   | 1,533                           |
| Light (L)                  | (10–20>                                               | 1,500                           |
| Medium (M)                 | (20–35>                                               | 1,416                           |
| Heavy (H)                  | > 35                                                   | 1,300                           |
Table 4. Organic carbon (C<sub>org</sub>) content in mineral soils of grasslands in Poland in the 0–30 cm layer

| Type of soil   | Number of samples | C<sub>org</sub> average content % | Standard deviation (SD) % | C<sub>org</sub> content |
|---------------|-------------------|-----------------------------------|--------------------------|------------------------|
|               |                   |                                   |                          | Minimum % | Maximum % |
| Total mineral | 703               | 2,44                              | 1,50                     | 0,26       | 8,64      |
| Very light    | 204               | 2,48                              | 1,57                     | 0,26       | 8,64      |
| Light         | 191               | 2,54                              | 1,60                     | 0,48       | 7,96      |
| Medium        | 216               | 2,31                              | 1,42                     | 0,58       | 7,49      |
| Heavy         | 92                | 2,46                              | 1,31                     | 0,41       | 7,12      |

Source: own study based on the KSChR results.
Table 5. The average content of organic carbon ($C_{org}$) in the 0–30 cm layer of mineral soils of grasslands in individual voivodships and on the scale of the entire country

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

Source: own study based on the KSChR results.
## Table 6. Organic carbon content in the 0–30 cm layer of organic grassland soils in Poland

| Type of soil* | Organic matter content in a layer of 0–30 cm % | Number of samples | $C_{\text{org}}$ average content % | Standard deviation (SD) % | $C_{\text{org}}$ content | Minimum % | Maximum % |
|--------------|-----------------------------------------------|-------------------|-----------------------------------|--------------------------|-------------------------|------------|-----------|
| Fully mineralized peat-muck | ≤ 3%                                           | 4                 | 1,35                              | 0,38                     | 0,81                    | 0,81       | 1,62      |
| Mucky        | (3-10%>                                         | 47                | 4,00                              | 1,05                     | 1,77                    | 1,77       | 5,74      |
| Marsh        | (10-20% >                                       | 52                | 8,23                              | 1,52                     | 5,97                    | 5,97       | 11,50     |
| Mineral-muck | > 20 %                                          | 54                | 18,77                             | 6,10                     | 11,72                   | 11,72      | 43,27     |
| Total organic|                                               | 157               | 10,42                             | 7,35                     | 0,81                    | 0,81       | 43,27     |

* Soil types of organic origin were distinguished on the basis of Okruszko 1998, with partial use of soil nomenclature given by Pieśniński, Gotkiewicz 1993.

Source: own study based on the KSChR results.
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 | $C_{\text{org}}$ average content % | Standard deviation (SD) % | $C_{\text{org}}$ content | Minimum % | Maximum % |
|-------------------------|-------------------|------------------------------------|---------------------------|--------------------------|-----------|-----------|
| Kuyavian-Pomeranian     | 11                | 8,54                               | 5,62                      | 3,85                     | 22,81     |
| Lublin                  | 4                 | 8,31                               | 11,35                     | 1,60                     | 25,29     |
| Lubusz                  | 9                 | 5,69                               | 3,93                      | 1,77                     | 13,74     |
| Łódź                    | 9                 | 10,53                              | 13,31                     | 0,81                     | 43,27     |
| Lesser Poland           | 1                 | 6,96                               | 0,00                      | 6,96                     | 6,96      |
| Masovian                | 19                | 12,09                              | 7,45                      | 3,55                     | 26,00     |
| Podlaskie               | 37                | 14,67                              | 5,87                      | 4,80                     | 24,64     |
| Pomeranian              | 18                | 7,68                               | 4,16                      | 2,64                     | 20,26     |
| Silesian                | 1                 | 5,74                               | 0,00                      | 5,74                     | 5,74      |
| Warmian-Masurian        | 31                | 11,25                              | 7,71                      | 2,68                     | 41,30     |
| Greater Poland          | 9                 | 2,77                               | 1,06                      | 1,36                     | 4,81      |
| West Pomeranian         | 8                 | 8,13                               | 3,95                      | 3,41                     | 15,26     |
| Poland                  | 157               | 10,42                              | 7,35                      | 0,81                     | 43,27     |

Source: own study based on the KSChR results.
Table 8. Assessment of organic carbon ($C_{org}$) content in grassland soils

| Content class | The share of GL soils in the $C_{org}$ content classes |  |
|---------------|------------------------------------------------------|--|
|               | according to the IUNG-PIB classification | according to the EDS classification |
|               | 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             |
Table 9. Organic carbon resources in the soils of grasslands in Poland in the 0–30 cm layer

| Type of GL soils | \( C_{\text{org}} \) average resources (Mg (t) · ha\(^{-1}\)) | \( C_{\text{org}} \) resources (Tg (million tons)) |
|------------------|-------------------------------------------------|-----------------------------------------------|
| Mineral          | 106,7                                           | 253,3                                         |
| Of organic origin| 251,2                                           | 159,4                                         |
| GL total         | 137,2                                           | 412,7                                         |

Source: own study.
Table 10. Organic carbon content of arable soils in the 0–20 cm layer [IUNG-PIB 2017]

| Specification | Average content of organic carbon in arable soils |
|---------------|-----------------------------------------------|
|               | Year  | 1995 | 2000 | 2005 | 2010 | 2015 | average 1995–2015 |
| n             |       | 216  |      |      |      |      |                  |
| C$_{org}$ %   | 1,13  | 1,14 | 1,09 | 1,14 | 1,12 |      | 1,12             |

Table 11. Pearson correlation coefficients between the average content of organic carbon $C_{org}$ in the 0–30 cm layer of mineral soils of grasslands in individual voivodships and the cows and cattle stock population in them per 100 ha of agricultural land (AL)

| Variables     | Cows stock rate head · 100 ha$^{-1}$ AL | Cattle stock rate head · 100 ha$^{-1}$ AL |
|---------------|----------------------------------------|------------------------------------------|
| $C_{org}$ %    | 0,578*                                 | 0,611*                                   |

Notes: correlation significant* for the significance level $\alpha = 0.05$ with the number of correlated pairs $n = 16$

Source: own study.
Table 12. Levels of significance of comparisons of the variable ‘organic carbon content (C_{org})’ between groups distinguished according to the category of mineral soils

| C_{org} content | p-Value for multiple comparisons (two-tailed) |
|-----------------|----------------------------------------------|
|                 | [independent (grouping) variable: ‘soil category’; Kruskal-Wallis test: H (3, N =703) = 3,706266; p = 0,2950] |
|                 | BL; R:354,15                               |
| VL              | 1,000000                                   |
|                 | L; R:360,34                                 |
|                 | 1,000000                                   |
| M               | 0,982481                                    |
| H               | 0,488384                                    |
|                 | S; R:332,25                                 |
|                 | 1,000000                                   |
|                 | C; R:376,30                                 |
|                 | 1,000000                                   |

Explanations: VL, L, M, H – symbols as in table 3; N – number of valid results, H – value of the Kruskal-Wallis test; p – level of statistical significance; R – average rank. Source: own study.
Table 13. Recommended depth of groundwater table location (GTL) due to the water needs of plants and inhibition of the loss of organic mass in peat-muck soils [based on: Jurczuk 2004]

| Moisture-soil complex | Recommended GTL depth (cm) due to the water needs of plants | inhibition of the loss of organic mass |
|-----------------------|-----------------------------------------------------------|--------------------------------------|
| Moist – B             | 55 cm                                                     | 25 cm                                 |
| Periodically dry – BC | 50 cm                                                     | 30 cm                                 |
| Dry – C               | 30–35 cm                                                  | 30–40 cm                              |

Notes: complex B – includes slightly and moderately rotten soils on deep, poorly and moderately decomposed peats; BC – includes medium and slightly rotten soils on slightly shallower, moderately decomposed peat; C – includes shallow and medium-deep peat-muck soils as well as mineral-muck, muck and black earth soils.
**Figure 1**

The relationship between the cows population per 100 ha of arable land and the content of organic carbon in mineral soils of grasslands. Explanation: codes for voivodships 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
Figure 2

The relationship between the cattle stock per 100 ha of arable land and the content of organic carbon in mineral soils of grasslands; explanations as for fig. 1. Source: own study

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