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The trend of changes in soil organic carbon content in Poland over recent years

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Abstract: The article analyzes soil organic carbon (SOC) content of in Poland from 2015 to 2021. The research aims to determine SOC levels and their dependence on soil agronomic categories and drought intensity. Soil samples from 1011 farms across 8 Polish voivodships were collected for analysis, all from the same agricultural plots. SOC determination was conducted using the Tiurin method. The results indicate a low SOC content nationwide (0.85-2.35%). Heavy soils exhibited higher SOC accumulation compared to light soils. Moreover, significant drought impact led to decreased SOC content in affected regions. Scientific evidence underscores a declining trend in organic carbon stock within agricultural soils, attributed to natural soil changes and unsustainable management practices. This decline is concerning given the crucial role of SOC in soil health, quality, and crop productivity. Therefore, it is imperative to monitor and address areas with low SOC levels to enhance SOC abundance. Furthermore, when used as a whole-cell biocatalyst in a low-cost upflow MFC, the Morganella morganii-rich SF11 consortium demonstrated the highest voltage and power density of 964.93±1.86 mV and 0.56±0.00 W/m3, respectively. These results suggest that the SF11 bacterial consortium has the potential for use in ceramic separator MFCs for the removal of penicillin and electricity generation.

Introduction

There is no doubt that the quantity of organic material is one of the essential criteria for soil quality. The preservation of this material is crucial for crop productivity. However, soil organic content is not constant; it is subject to numerous fluctuations. The level of SOC is influenced by two fundamental factors: the supply of organic material over a given time period and the rate of mineralization that occurs in the soil. In Polish environmental conditions, several factors negatively affect the amount of organic mass and its mineralization. One of such factors is drought, which inhibits the arrival of organic mass and slows down the mineralization process due to water deficits in the soil. Despite organic carbon arriving in many Polish light and heavy soils over recent decades, the balance remains unfavorable in many voivodships. This imbalance can be attributed, among other things, to insufficient manure and deficits in natural fertilizers. Naturally, the accumulation of organic carbon also depends on the sorption complex in various farms (Jaskulski 2017, Pietrzak and Hołaj-Krzak 2022).

There are currently many methods to increase the amount of organic carbon in the earth. One of the practiced solutions is to include in the plan crops that facilitate increased biomass in the soil. Roots and remnants of agricultural crops remain in the soil, which in practice may have a beneficial effect on the accumulation of organic matter in question.

It is equally important to ensure that the soil preserves its germinative structure, as well as to manage water resources adequately. Soil quality is also affected by the rotational crop model and the use of fertilizers, which allows for the maintenance of the water's pH at an optimal level (Lal 2006).

A number of factors determine the amount of organic carbon in the soil. Various factors were mentioned, such as the amount of water, temperature, and soil structure. An increase in temperature leads to the evaporation of water resources in the soil, thereby negatively affecting the level of organic carbon. However, the level of organic matter in the earth is also strongly influenced by anthropogenic factors - actions taken by humans to increase air supply to the earth. These actions, in turn, lead to an increase in temperature, which accelerates the process of mineralization, resulting in the loss of organic carbon. During mineralization, organic carbon is reduced and released in gas form (Lenart 2013).

In the field of agrotechnology, which shapes the level and quality of crops, crop modelling and fertilization should be taken into account. Human activity can alter the physico-chemical and structural properties of soil in terms of air-water relations and permeability. All of these factors affect the level of organic carbon. Actions such as crushing, tilling, mixing, and compacting are reasonable. In this context, it is worth paying attention to direct sowing, which leaves almost 90 percent of the residues on the surface of the field. This practice has a beneficial effect on the formation and accumulation of carbon (Martyniuk 2019).

It is essential to consider that solutions aimed at preserving biodiversity in the cultivation environment are beneficial for the level of organic carbon in the soil. The duration of soil regeneration periods is also important. Fertilizers play a significant role in shaping soil properties. Considering all available factors influencing the reproduction and degradation of organic matter, it can be concluded that certain plants grown in specific environments may either increase or decrease the accumulation of organic material (Ochal 2017).

The question remains, why is organic carbon such an important factor in determining the quality and quantity of harvests. In agricultural settings, it is highly recommended to regularly test the soil's fertility and its saturation with essential macronutrients. Organic carbon, meanwhile, stands out as one of the essential components of soil health, greatly benefiting its overall quality. It influences soil fertility and the abundance of microorganisms and enzymes, thereby contributing to the effectiveness of plant growth in a given area.

However, the level of organic matter in the soil continues to decline, primarily due to human activity. This decline is not only a result of detrimental actions but also of the absence of proactive measures. The excessive industrialization and chemicalization of agriculture significantly contribute to this issue. Farmers often overlook the use of fertilizers beneficial to the soil, and the problem of excessive plowing exacerbates the loss of organic matter through soil aeration. While good practices aimed at increasing organic carbon content are promoted in the agricultural sector through financial programs and subsidies, their effectiveness remains unsatisfactory. Only a few large and highly modernized enterprises are inclined to adopt beneficial fertilizers and agricultural production models.

All factors affecting soil organic matter, with a particular focus on organic carbon, will be further analyzed. This paper seeks to identify the reasons for poor soil condition and explore methods to address this situation. The quality of the soil will be presented in a quantitative, statistical manner, aiming for maximum objectivized.

Research on organic carbon in soil is extremely important for sustainable agriculture and environmental protection. Soil serves as a substrate for plants, facilitating various processes and supporting diverse organisms that interact with each other. Organic carbon, a fundamental component of soil, affects its structure, physical properties, and capacity to terrain water and nutrients (Nasiri et al., 2023). This knowledge is of great importance for the development of farming practices that prioritize sustainability in the face of environmental and climate challenges. Enhancing the soil's ability to retain organic carbon in its upper layers directly mitigates carbon dioxide emissions into the atmosphere, a crucial factor affecting global warming and promoting sustainable agricultural production (Gerke 2022, Lal et al. 2007, Lipiński et al. 2020).

Soil organic matter (SOM) contains more than three times as much carbon as the atmosphere or terrestrial vegetation, making it an important component of the global carbon cycle. SOM comprises organic residues of plant or animal origin and is essential for sustaining vegetation. It has many functions, including increasing water retention, increasing air permeability, improving soil structure, providing nutrients for plants and microorganisms, and regulating soil pH (Kuś 2015, Siuta 1995, The Intergovernmental Panel on Climate Change 2022). Organic matter is also important from an environmental standpoint because its presence in the soil affects the soil's ability to retain organic carbon. When discussing SOM in the context of organic carbon abundance, it is worth mentioning soil humus (HS), which has recently posed challenges due to the consideration of biological factors in its formation processes (Giachin et al. 2017).

Recent studies have shown that HS constitutes a significant portion of soil organic carbon (SOC). Some estimates suggest that humus accounts for 50 to 80% of the organically bound carbon in the soil (Gerke 2022). The role of HS in stabilizing soil organic carbon is pivotal for maintaining soil fertility and mitigating climate change. HS aids in shielding organic carbon from microbial degradation by forming stable complexes with organic molecules and minerals in the soil (Amoah-Antwi et al. 2022). Moreover, HS contributes to soil structure aggregation, enhancing soil water retention, nutrient availability, and promoting plant growth (Giachin et al. 2017). Therefore, understanding the mechanisms underlying HS formation and stabilization is crucial for organic carbon management and soil improvement.

SOC sustainability plays a vital role in maintaining ecosystems health. The alteration of soil organic carbon stocks by biotic activities of plants and microorganisms can significantly impact soil function and productivity (Dignac et al. 2017). Additionally, SOC degradation may result in reduced soil productivity and adversely affect carbon sequestration efforts (Nachtergaele et al. 2016). The concept of persistence of soil organic carbon (SOC) is a new concept in soil science, gaining prominence due to its implications for ecosystem properties (Schmidt et al. 2011). Understanding this property of SOC is crucial for advancing soil science and appears to be essential for maintaining healthy ecosystems. Persistence of soil organic carbon refers to the duration organic carbon remains in the soil before undergoing decomposition or loss (Schmidt et al. 2011).

The implications of SOC persistence for soil carbon sequestration are significant. Soil carbon sequestration involves capturing atmospheric carbon dioxide and retaining it in the soil, thereby aiding in climate change mitigation. However, the effectiveness of soil carbon sequestration initiatives hinges directly on SOC persistence (Dynarski et al. 2020). Incorporating methods to enhance SOC persistence into agricultural practices can bring numerous benefits. Regenerative agricultural practices, aimed at enhancing soil health and increasing organic matter content, offer one such avenue (Newton et al. 2020). These practices, which include

Figure 1. Location of pairs of research points from farms.

the use of cover crops, crop rotation, and reduced tillage, can bolster agricultural productivity, reduce greenhouse gas emissions and promote sustainable land use (Giachin et al. 2017, Intergovernmental Panel on Climate Change 2022).

Traditional models of soil organic matter (SOM) dynamics have focused on transformations between defined SOM components (Robertson et al. 2019). However, the durability of SOCs highlights the importance of including a continuum of organic fragments susceptible to abiotic oxidation and enzymatic hydrolysis, ultimately metabolized by microorganisms and plants (Cotrufo and Lavallee 2022). By incorporating this concept, soil research can provide a more comprehensive understanding of SOC's role in ecosystem processes and inform management practices aimed at promoting long-term carbon retention in the topsoil (Castañeda-Gómez et al. 2023).

The organic carbon content of soil is also important for plant health and crop quality. Soils rich in SOC tend to have a higher content of nutrients such as nitrogen, phosphorus and potassium, which contributes to better plant growth and development. In addition, SOC helps regulate pH levels and improves soil structure, facilitating better water and nutrient absorption by plants (Nasiri et al. 2023, The Intergovernmental Panel on Climate Change 2022).

Carbon sequestration, a natural process involving the removal of carbon from the atmosphere and its storage in soil and vegetation, is critical for mitigating climate change (Gonet and Markiewicz 2007). Thus, maintaining the proper balance of organic matter and organic carbon in soil is essential, achievable through agricultural practices such as applying organic fertilizers, crop diversification, using green manure management systems, and crop rotation (Francaviglia et al. 2023).

The protection and increase of soil organic carbon resources have gained prominence in the environmental and agricultural policy of the European Union. Member States are mandated to implement various measures to increase soil carbon stocks. For this reason, national and regional monitoring of soil resources, particularly organic carbon content, holds significant importance. This emphasis is evident in the EU's new strategy, the European Green Deal, which addresses soil degradation and land resource protection. Increasing soil organic matter content emerges as a key approach to enhancing soil condition (The European Green Deal 2019).

The article analyzes the results of the organic carbon content in soils (SOC).The first aim of the article was to provide information about the role of carbon in the environment for practical use in sustainable agriculture. The second aim of the research was to examine the level of SOC and determine its dependence on the agronomic category of mineral soils, pH, and the presence or absence of rainwater. Another goal was to use the results as a reference point for further research on soil quality improvement through the use of innovative fertilizers containing ash from biomass combustion in a three-year field experiment.

Materials and Methods

Soil samples were collected from arable land on farms that conducted soil tests at Chemical and Agricultural Stations in Białystok, Gdańsk, Gliwice, Olsztyn, Łódź, Rzeszów, and Wrocław. Data were collected from 1011 farms across 8 voivodships in Poland: Dolnośląskie (132), Lubelskie (44), Łódzkie (420), Mazowieckie (26), Podkarpackie (118), Podlaskie (31), Śląskie (72) and Warmińsko-Mazurskie (168).

As a criterion for the selection of samples, the availability of complete data for analysis was adopted, including data from the same fields collected at two study dates three years apart. These voivodships differ in topography and temperature distribution, leading to variations in the beginning of the growing season and the amount of precipitation during the growing season.

Data on areas affected by drought in Poland in 2015-2021 were obtained from the Agricultural Drought Monitoring System, developed by the Institute of Soil Science and Plant Cultivation - National Research Institute in Puławy. This system integrates meteorological data collected from measurement points of the Institute of Meteorology and Water Management. The Drought Monitoring system calculates the climatic water balance and utilizes data from the digital soil and agricultural map, depicting the spatial differentiation of water retention across various agronomic soil categories. The climatic water balance represents the difference between precipitation and potential evapotranspiration.

Soil samples for testing were collected on two dates from the same areas of arable land between the years 2015 and 2021. The analysis focused on mineral soils categorized as heavy (including medium and heavy clay, clay dust, loam, dusty loam), medium (encompassing light clay and light dusty clay), light and very light soils (comprising clay sand, dusty clay sand, ordinary dust).

To illustrate trends in SOC content over the analyzed period, the research results are presented as medians from two periods: SOC1 covering the years 2015-2018, and SOC2 covering the years 2019-2021. Soil acidity was evaluated based on the limit values specified in the Polish standard PN-ISO 10390, with pH determined in a solution of 1 mol KCl·dm$^{-3.}$ The soils were classified into 5 groups based on pH in KCl solutions: very acidic (pH < 4.5), acidic (pH 4.6–5.5), slightly acidic (pH 5.6–6.5), neutral (pH 6.6–7.2), and alkaline pH > 7.2. The results of soil pH and soil agronomic categories are presented as medians for the two study periods.

Soil samples were collected each year of the study using soil sticks (Egner) from a depth of 0-20 cm. At designated locations, the stick was inserted vertically into the soil until it met resistance, rotated fully, and then removed. The collected soil samples were transferred to separate containers, thoroughly mixed, and any plant debris, small stones and other impurities were removed. Aggregate samples, weighing approximately 500 grams each, were a mixture of an average of 15 incremental samples taken from evenly distributed points in the study area, not exceeding 4 ha in size, and excluding field edges, furrows, depressions or steep hills.

The agronomic category of the soil was determined using the organoleptic method, which involves observing the sample in its natural state and determining its behavior when rubbed between fingers in a wet state during field research (Ryżak et al. 2009), and then verified at Regional Chemical and Agricultural Stations. Soil analysis was performed in duplicate on samples passed through a sieve with a mesh size of 2.0 mm.

Soil pH was determined in a soil suspension with a concentration of 1 mol·dm^{-3} of potassium chloride. The Tiurin's method was used to determine the organic carbon content, based on wet combustion (oxidation) of organic matter (Breś et al. 1997). In this method, a soil sample placed in a strongly acidic solution of sulfuric acid was treated with a specified amount of potassium dichromate ($K_2Cr_2O_7$), which oxidized organic compounds in the soil. The remaining potassium dichromate in the solution was titrated with Mohr's salt (Fe (NH_2)SO_4 · $6H_2O$) to determine the percentage of carbon in the soil. As a reference point, the so-called 'zero measurement' was conducted wherein quartz sand, pumice or loess sand roasted at 900°C was analyzed instead of soil, representing material without carbon (Łądkiewicz et al. 2017). The selection of the Tiurin method for organic carbon determination was based on the technical capabilities of the laboratory in 2015. In the following years, the analyzes were continued with the same method to ensure comparability of results over time.

When comparing soil organic matter (SOM) information, it is assumed that:
• 1% SOM = 0.58% soil organic carbon (SOC);
• 1% soil organic carbon (SOC) = 1.72% SOM.

The European Soil Bureau (ESB) adopts the following criteria for assessing organic carbon content in European soils ("COMMUNICATION FROM THE COMMISSION TO THE COUNCIL, THE EUROPEAN PARLIAMENT, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - Thematic Strategy for Soil Protection" 2006):
• very low <1.0% SOC = <1.72% SOM;
• low 1.1–2.0% SOC = 1.72–3.44% SOM;
• medium 2.1–6.0% SOC = 3.44–10.32% SOM;
• high >6.0% SOC = >10.32% SOM.

It was also assumed that for soils containing less than 2.0% SOC (3.4% SOM), the method of their use should be defined and introduced to increase the content of organic matter. These soils were considered to be at risk of desertification (Giachin et al. 2017, Kiryluk and Kostecka 2023, Rusco et al. 2001).

The obtained data on the soil's organic carbon content did not meet the assumption of normal decomposition (Shapiro-Wilk test). Therefore, non-parametric tests were used to compare its content in subsequent years. The Wilcoxon Matched Pairs Test for paired samples was used for the analysis by province and soil category. Additionally, the Mann-Whitney U test was applied to analyze changes related to soil acidity, which was subject to changes in the adopted classification. All analyzes were performed using the Tibco Statistica v.14 program, and a significance level of $\alpha=0.05$ was assumed in the tests. Statistically significant differences were highlighted in red.

Results

The SOC content did not differ statistically significantly between the examined time points in the Dolnośląskie, Lubelskie and Śląskie voivodships (Table 1). However, in the remaining voivodships, a statistically significant difference was observed between the first and second surveys at three-year intervals from 2015 to 2021.

Table 1. Results of statistical analysis of differences in organic carbon (SOC) content at time points 1 and 2 (Wilcoxon test).

Voivodship	Number of sampling points at each time-point	p-value
Dolnośląskie	132	0.265
Lubelskie	44	0.513
Łódzkie	420	≤0.05
Mazowieckie	26	≤0.05
Podkarpackie	118	≤0.05
Podlaskie	31	≤0.05
Śląskie	72	0.148
Warmińsko-Mazurskie	168	≤0.05

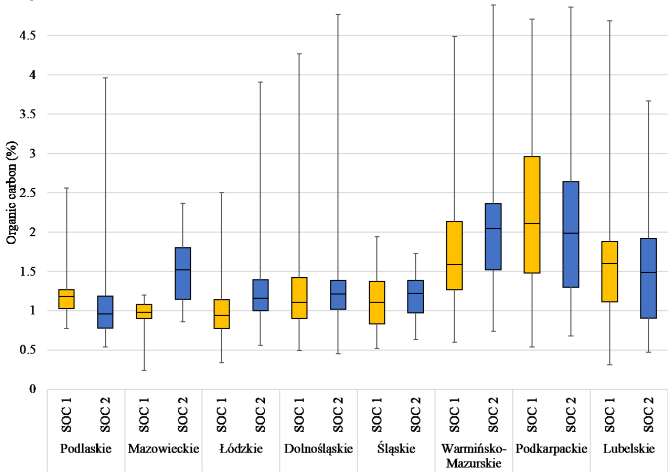

Figure 2. Box plot of organic carbon content depending on the voivodship and sampling period in 2015-2021.

The organic carbon content varied across the regions studied of Poland, with most regions showing SOC content well below 2%. (Chart 2). The SOC content in the surveyed voivodships ranged from 0.96 to 2.11%, with the highest levels observed in the Podkarpackie Voivodship (SCO 1, the initial phase of the study) and Warmińsko-Mazurskie (SOC 2, the second phase of the survey after three years). The greatest increases in SOC during the three-year research cycle were recorded in the Mazowieckie (+0.54%), Warmińsko-Mazurskie (+0.46%), and Łódzkie (+0.22%) voivodships. Conversely, decreases in organic carbon content between SOC 1 and SOC 2 was observed in Podlaskie (-0.22%), Podkarpackie (-0.12%) and Lubelskie (-0.15%) voivodships.

In the Podkarpackie Voivodship, which exhibited highest SOC content, no drought was recorded during the period of 2015-2021. (Fig. 3). Conversely, in the Mazowieckie Voivodship, where the greatest increase in SOC was recorded, favorable changes in soil moisture conditions were noted. On the contrary, in the central and western regions of the country, experiencing a significant decrease in SOC, an increase in the proportion of areas affected by drought was observed throughout the analyzed period.

Figure 4 shows the variation in SOC content over the three-year intervals of the tests, categorized by soil pH. In alkaline soils, the SOC content remained stable (Table 2, no statistically significant difference) whereas statistically significant differences were observed in other soil types. Across all pH ranges - very acidic, acidic, slightly acidic, neutral and alkaline - an increase in the SOC content was observed during the three-year testing period. The highest SOC content (+0.28%) was observed in alkaline soils, while the lowest SOC content was found in very acidic and acidic soils.

Table 2. The results of satatistic analysis of SOC content in relation to soil pH between years, because the pH value changes over time, therefore the measurements are treated independently (Mann-Whitney U test).

Soil acidity	p-value
very acidic (below 4.5 pH)	0.0193
acidic (4.6-5.5 pH)	0.0000
slightly acidic (5.6-6.5 pH)	0.0014
neutral (6.6-7.2 pH)	0.0000
alkaline (above 7.3 pH)	0.3550

Figure 5 illustrates the SOC content in soils categorized by agronomic types. The SOC content in light soils did not exhibit statistically significant differences in subsequent years of the study (Table 3). However, statistically significant variations in SOC content were observed in the remaining light, medium and heavy soils (Table 3). During the initial SOC 1 research period, the accumulation of organic carbon in heavy soils reached 2%, while it was lowest in very light soils at 1.2%. Over the three-year research interval, the highest increase in SOC content was recorded in light fiefs (+0.21%), whereas a decrease was noted in heavy soils (-0.18%). Heavy soils possess higher sorption capacity, retaining water and nutrients more effectively than lighter soils. This capacity promotes favorable plant development, resulting in increased accumulation of organic

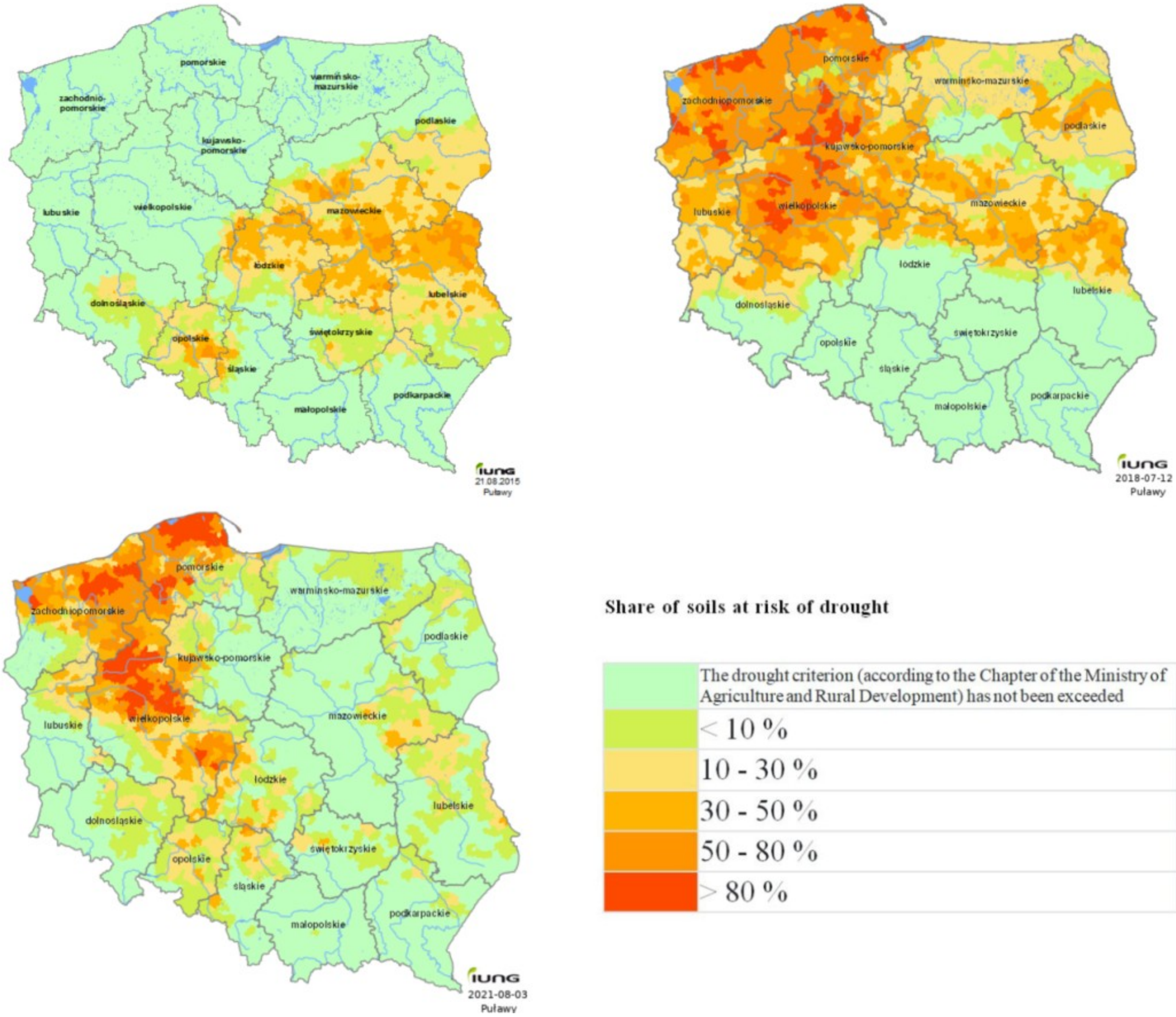

Figure 3. Polish areas affected by drought over the years 2015-2021 (https://susza.iung.pulawy.pl).

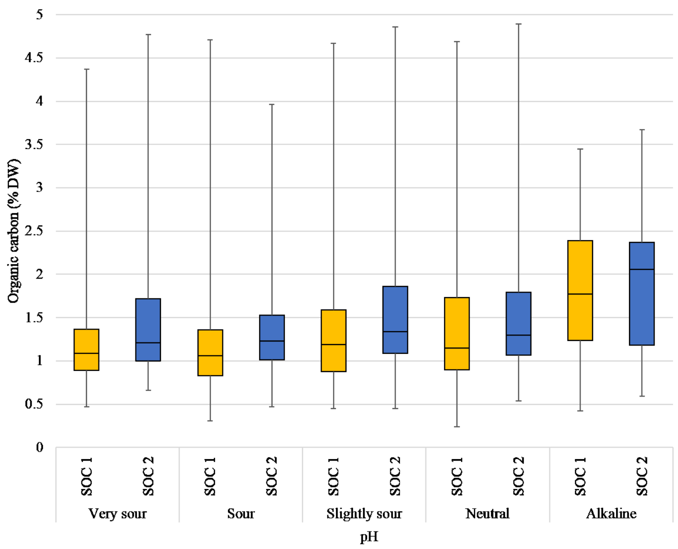

Figure 4. Box plot of organic carbon content depending on pH value and sampling period in 2015-2021.

carbon within their structure. Additionally, heavy soils exhibit lower water permeability, leading to greater water retention, which in turn supports the growth of microorganisms involved in organic matter formation and decomposition.

Figure 6 shows the accumulation of organic carbon in soils with varying acidity levels, categorized according to agronomic types. Among heavy soils exhibiting a very acidic reaction, the

Table 3. The results of statistical analysis of differences in organic carbon content (SOC) depending on the agronomic category of soils at time points 1 and 2. (Wilcoxon test).

Category of soil	Number of sampling points at each time-point	p-value
very light	23	0.0629
light	586	<0.001
mean	251	0.0008
heavy	151	0.030

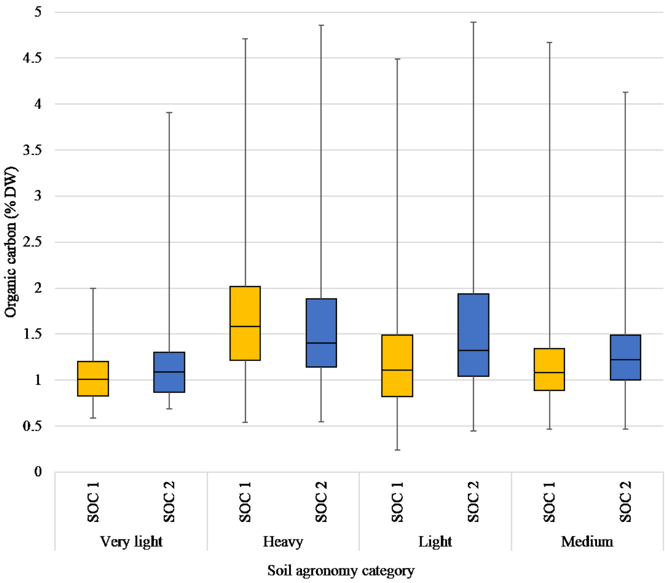

Figure 5. Box plot of organic carbon content depending on soil agronomic category and sampling period in 2015-2021.

highest SOC content was observed, with the most significant increase in the content in a three-year interval. Conversely, very light soils on alkaline substrates demonstrated the lowest SOC content, often below 1% . In the case of other soils, there was a general trend of increasing SOC content with higher soil pH levels, a pattern prominently observed across all pH ranges of light soils.

Discussion

Organic carbon, a component of organic matter, affects various physical, chemical and biological processes in soil. Soil Organic Matter (SOM) serves as a crucial structural component of the soil, impacting its porosity, permeability, as well as water and nutrient storage capacity. Research underscores organic carbon's pivotal role in enhancing soil porosity (Ochal, 2017). Additionally, SOC serves as an energy source for soil organisms, such as bacteria, fungi and protozoa, which facilitate organic matter decomposition and nutrient enrichment (Nasiri et al., 2023; The Intergovernmental Panel on Climate Change, 2022). Scientific evidence shows that organic carbon stocks in the top layers of agricultural soils are diminishing globally. According to the 2022 Intergovernmental Panel on Climate Change (IPCC) report, global soil organic carbon stocks decline annually by 0.25-0.75%. In Europe, approximately 45% of land exhibits low organic carbon content, as reported by the European Soil Data Centre. This trend reflects the broader situation in Polish agriculture. These figures are alarming considering soil organic carbon stocks' significance in maintaining soil health, quality, and consequently, crop productivity (The Intergovernmental Panel on Climate Change, 2022). Research indicates that plant growth is determined by organic carbon content, underscoring its economic importance. Therefore, the lack of emphasis on researching soil organic carbon content among many farmers is concerning (Pikuła, 2013).

In Poland, the assessment of SOC content employs specific criteria, particularly crucial given the prevalence of light soils, mainly composed of various types of sands. These soils tend to experience rapid mineralization of organic compounds, limiting the potential for SOC accumulation. Approximately 56% of agricultural land in Poland exhibits low to medium SOC content, typically in the range of 0.58-1.16% SOC. According to the assessment criteria of the European Soil Bureau (ESB), these soils are categorized as having very low SOC content. Another 33% of agricultural land contains SOC levels between 1.17 and 2.03%, which, though considered high in the local context, falls into the low SOC content class according to ESB classification. Higher SOC concentrations, exceeding 3.5%, are primarily found in specific soil types such as chernozems, black earths, rendzinas, and heavy alluvial soils, constituting approx. 11% of all soil types in Poland (Schmidt et al. 2011).

Polish soils exhibit relatively low levels of SOC, a factor that necessitates careful consideration when managing by-products and selecting suitable crop species. Predominantly, wheat, maize, and rapeseed are the most commonly grown plants in Poland, requiring soil with high rate of caries. Recent years have seen a slight increase in the average SOC content in Poland. However, the tested SOC values generally range from 0.96to 2.11%, classified as low SOC according to the European classification. Consequently, the environmental conditions in Poland pose challenges for agricultural development (Sapek 2016). Well-cultivated and maintained soils typically boast higher organic matter levels. Nevertheless, intensive agricultural practices can lead to a significant reduction in soil organic matter content (Siuta, 1995).

Natural variation in SOC content is determined by several factors such as particle size distribution, field location, and water conditions. Importantly, analyses carried out in this paper show that all these factors influence each other and strengthen their action. Light soils situated at higher altitudes, beyond the reach of groundwater, are usually characterized by lower SOC content compared to compact soils with soil-precipitation management. The highest content of organic matter is found in alkaline soils developed in water-dependent habitats, such as chernozem and peat soils. Among anthropogenic factors, land use (e.g., agricultural, meadow, forestry), agricultural intensification, crop rotation, the presence of catch crops, and level of organic fertilization significantly impact soil organic matter content. The analysis carried out in this study highlights the substantial role of farmers, particularly through crop rotation practices, in enhancing organic carbon levels (Małecka 2018). Higher organic carbon content also corresponds to increased levels of humus compounds, which, owing to their sorption capacity, contribute to maintaining relatively constant soil pH levels (Cotrufo and Lavallee 2022).

Analysis of soil SOC in relation to soil pH reveals a slight upward trend towards alkaline pH (Figure 3). Soils with alkaline pH levels tend to harbor a great abundance of soil microorganisms, promoting organic matter decomposition and enhancing soil biological activity. Consequently, alkaline soils may have exhibit higher organic carbon content. However, differences in organic carbon content based on soil pH are typically minor. Other factors such as soil type, climate, and agricultural practices have a greater impact on soil organic carbon content than soil pH. Research shows that soil condition and crop quality are primarily influenced by the physical and chemical properties of the soil. Soil structure, characterized by permeability and binding capacity, plays a crucial role in

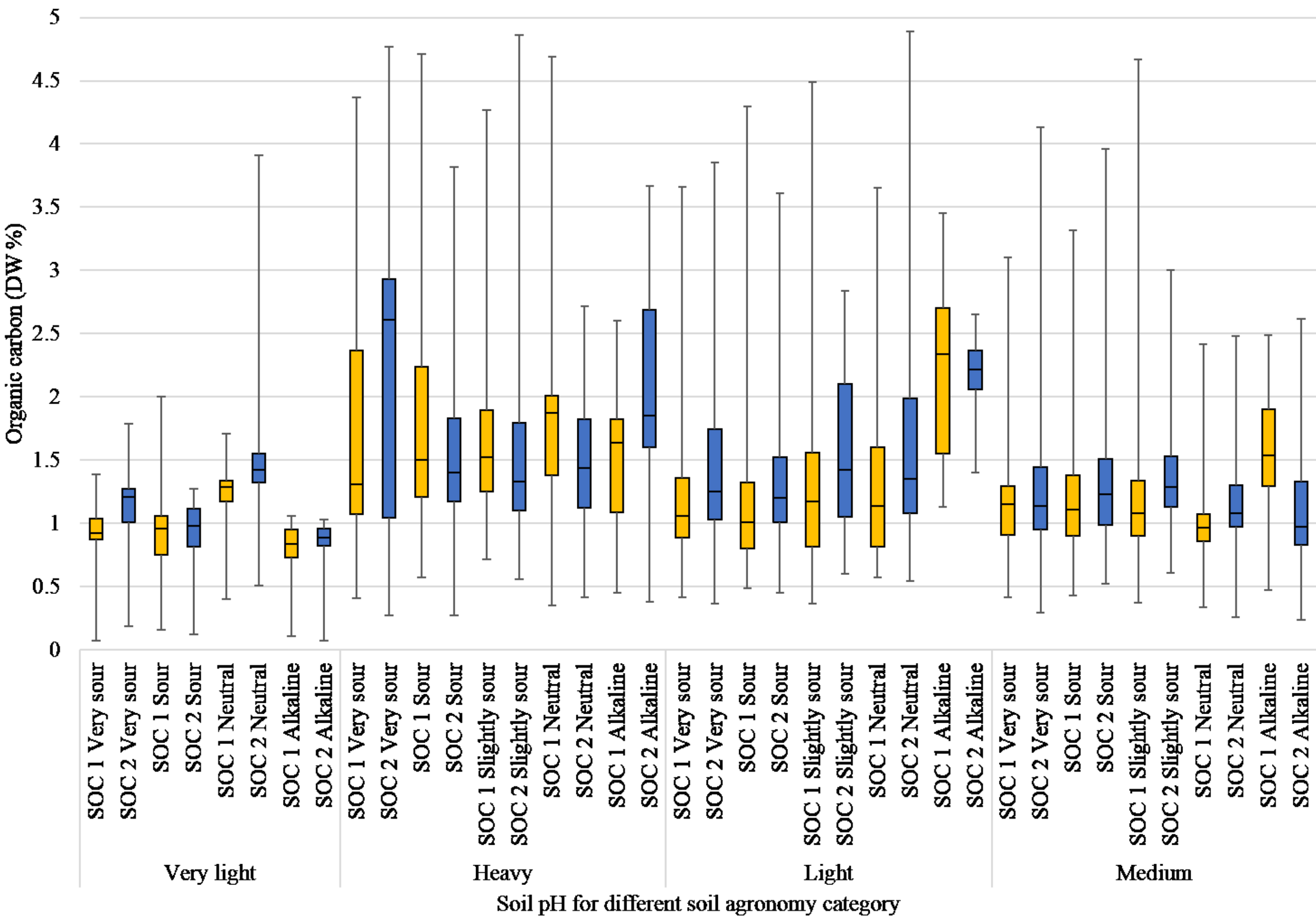

Figure 6. Box plot of the content of organic carbon depending on the pH value for particular agronomic soil categories in 2015-2021.

determining soil health and crop productivity. Finally, human intervention and agricultural practices significantly shape soil health and organic carbon dynamics.

In Poland, ongoing activities aim to bolster organic matter supply through practices like catch cropping, straw incorporation during plowing, and the use of organic fertilizers. Efforts are also underway to curtail decomposition rates, including measures such as limiting nitrogen application from natural fertilizers to 170 kg/ha or reducing or eliminating certain crops. Several studies emphasize the adverse effects of nitrogen deficiency on crop quality, manifesting in shortened and weakened stems, decreased chlorophyll levels, and a truncated vegetation period. Consequently, nitrogen fertilization is necessary in each year following crop sowning (Małecka 2018). For years, Regional Chemical and Agricultural Stations and Agricultural Advisory Centers have been supporting local agriculture, encouraging farmers to improve the quality of soils both in terms of both physical characteristics and the nutrient content. However, analyses conducted in this study show that this kind of activity is not sufficiently effective. Many farmers overlook the importance of continuous soil quality assessments, hindering the ability to identify needs and implement appropriate measures.

Soil fertility tests, especially those assessing SOC, are relatively rarely performed by individual farms in Poland. The decentralized nature of Polish agriculture, characterized by the absence of unions or conglomerates of large enterprises, largely shapes this trend. The structure of agriculture in Poland, marked by farm fragmentation and their low profitability, often dissuades farmers from conducting thorough soil analyses. Typically, only basic parameters such as pH, potassium, phosphorus, and magnesium content are tested. Meantime, various other methods, including assessment of sulfur levels, remain underutilized. These analyses are most often performed in accredited laboratories of Regional Chemical and Agricultural Stations. Economic considerations pose a significant obstacle to determining SOC content, with full-scale analyses typically undertaken every two or three years in large, modern farms, and even less often in smaller operations every year. This trend is concerning, particularly considering that soil quality studies and improvement measures are less frequently pursued in smaller farms (Smagacz 2011).

Each type of soil has its own distinct properties that affect its capacity to retain organic carbon, a factor intricately linked to its agronomic classification, which in turn reflects its physical and chemical properties. In heavy soils, a greater proportion of floatable particles brings the particles closer together, which hinders the movement of water and air. Consequently, organic carbon in heavy soils is less prone to erosion and remains more stable, facilitating long-term storage within the soil matrix. On the other hand, sandy soils feature greater paticle spacing, rendering them more permeable and have less adept at retaining water and organic matter. These spaces within sandy soils can expedite organic matter decomposition by microorganisms, leading to faster release of CO_2 into the atmosphere and a consequent reduction in soil organic carbon levels (Myśleńska 2001).

Research findings corroborate these relationships, with soil density emerging as a critical factor in stabilizing organic matter levels over time. In soils with higher permeability, including sandy soils, organic material, including organic carbon, undergoes faster decomposition. All this affects the plant growth and the selection of suitable crops for specific environmental conditions. However, without comprehensive soil quality studies, it may not be possible to make the right assumptions (Kwiatkowska 2017).

Maintaining appropriate soil pH is crucial for sustaining the activity of microorganisms and enzymes responsible for improving the availability of nutrients and the decomposition of organic matter. The optimal pH range for increasing soil organic carbon typically falls between 6.0 and 7.5. However, it is important to recognize that soil pH is only one of many factors affecting organic carbon content and its impact may vary depending on other soil properties such as structure, moisture, climate and vegetation (Lipiński et al. 2020). This type of changes can result from both natural processes and human activities. For instance, drought conditions, coupled with common agricultural practices like frequent plowing and straw incorporation, especially on light soils, can impede straw decomposition due to moisture deficit. Much of Poland features soils derived from acidic sedimentary rocks, where alkaline cations have been intensively leached out. Precipitation and low temperatures, especially during autumn and winter, exacerbate these leaching processes. Soil pH deterioration can also occur due to the use of physiologically acidic fertilizers and the uptake of alkaline cations by crops (Pikuła and Rutkowska 2017). Studies show that farmers can significantly raise soil pH levels by selecting appropriate fertilizers, such as calcium-based fertilizers. This is important because inadequate PH levels diminish the soil's capacity to absorb and retain essential nutrients for microbial activity (Pikuła 2017).

Conclusions

The discussed issue of changes in the content of organic carbon, both in relation to the agronomic category and pH of the soil in the two studied periods, indicates that fluctuations in carbon content in individual regions largely depend on the soil management practices on the farm. Analyzing the maps of drought occurrence in the research period, it can be concluded that soil moisture conditions significantly impact the accumulation of SOM. In areas affected by drought, a decrease in SOC content was observed. The research results are of great importance for agricultural practice and indicate the need to take action to increase the soil's abundance of SOC, e.g., through proper soil management, such as the use of organic fertilizers and proper tillage techniques. In addition, an interesting direction aimed at improving soil quality in terms of SOC abundance involves investigating the possibilities of using innovative fertilizers containing ash from biomass combustion.

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Tendencja zmian zawartości węgla organicznego w glebach Polski na przestrzeni ostatnich lat

Streszczenie: W artykule dokonano analizy zawartości węgla organicznego w glebie (SOC) w Polsce w latach 2015 - 2021. Celem badań było określenie poziomu SOC oraz określenie jego zależności od kategorii agronomicznej gleby, odczynu i zawartości wody w glebie. intensywność suszy w glebie. Dane do analizy zawartości SOC uzyskano poprzez pobranie i analizę prób glebowych z 1011 gospodarstw zlokalizowanych na terenie całej Polski w 8 województwach Polski. Próbki gleby do badań pobierano co roku z tych samych powierzchni rolniczych. Oznaczenie SOC przeprowadzono metodą Tiurina. Wyniki testów wykazały niską zawartość SOC w całym kraju (0,85-2,35%). Lepsza. Większą kumulację zawartości SOC stwierdzono na glebach ciężkich w porównaniu z glebami lekkimi. Stwierdzono duży wpływ suszy na spadek zawartości SOC w rejonach jej występowania. Dowody naukowe wskazują, że zasoby węgla organicznego w górnych warstwach gleb rolniczych są niskie i nadal maleją w wyniku naturalnych zmian w glebie i niezrównoważonej gospodarki. Z danych naukowych wynika, że zasoby węgla organicznego w górnych warstwach gleb rolniczych zmniejszają się. Jest to szczególnie niepokojące, ponieważ zasoby SOC są ważnym czynnikiem wpływającym na zdrowie i jakość gleby, a tym samym na wydajność upraw. Z tego powodu bardzo ważne jest monitorowanie i identyfikowanie obszarów o niskim poziomie SOC oraz podejmowanie działań w celu poprawy obfitości SOC.