Current Agronomy

IUNG

doi: 10.2478/cag-2025-0010

Current Agronomy
(formerly Polish Journal of Agronomy)
2025, 54/2: 118–128

The impact of cover crops on soil quality

Beata Bartosiewicz, Rafał Wawer, Ludwika Poręba, Grzegorz Siebielec*

Department of Soil Science and Environmental Analyses, Institute of Soil Science and Plant Cultivation – State Research Institute
ul. Czartoryskich 8, 24-100 Puławy, POLAND

*Corresponding author: e-mail: Beata.Bartosiewicz@iung.pulawy.pl

Abstract. The aim of this study is to review the current state of knowledge regarding the role of cover crops as nature-based solutions (NBS) in agriculture. The analysis includes scientific literature from the years 2000–2024, primarily sourced from the Mendeley and Web of Science databases, using keywords such as cover crops, catch crops, nature-based solutions, soil health. The review focuses on research conducted in Europe and examines the multifaceted effects of cover crops on selected physical, chemical, and biological properties of soil. Cover crops have been shown to reduce soil bulk density, improve aggregate stability, and enhance water retention capacity, thereby increasing soil resilience to climate change. Additionally, they enrich soil with organic matter, leading to increased levels of soil organic carbon, and reduce nutrient losses (notably nitrogen and phosphorus), which helps protect the quality of groundwater and surface water. Cover crops also stimulate biological activity in the soil, enhancing its fertility and the efficiency of nutrient cycling. The paper also considers potential risks associated with their use, such as soil desiccation and the spread of diseases. This article provides a structured synthesis of the potential benefits and limitations of cover crops in the context of promoting sustainable agriculture.

Key words: aggregate stability, bulk density, cover crops, microbiological activity, nitrogen content, organic matter, pH, phosphorus content, water retention

INTRODUCTION

Modern agriculture faces numerous challenges, including a changing climate, declining biodiversity, soil degradation, and the necessity to increase agricultural production (Abdalla et al., 2019). Soil is an essential resource for food production. In the European Union, agricultural land occupies approximately 50% of the total area. As a non-renewable resource, protecting soil functions and preventing its degradation has become one of the priorities of the Common Agricultural Policy (https://agriculture.ec.europa.eu). Furthermore, the European Commission has set an ambitious target: by 2030, 75% of all European soils should be healthy (Veerman et al., 2020). This has necessitated the development of guidelines for soil and crop management practices that reduce the environmental footprint while helping farmers adapt to new conditions. In response to these challenges, the European Commission has introduced a soil protection strategy that promotes numerous agricultural practices positively impacting soil functions. This strategy has significantly influenced the shape of the reformed Common Agricultural Policy (CAP) (https://agriculture.ec.europa.eu). As a result, greater emphasis is being placed on nature-based solutions (NBS) aimed at protecting nature and the climate while maintaining healthy soils and productive agricultural systems (Sonneveld et al., 2018).

Nature-based solutions in agriculture represent an approach that leverages natural processes to increase efficiency while minimizing environmental impact. This strat-

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

egy focuses on restoring and strengthening soil functions critical to its health, such as nutrient cycling, water retention, and biodiversity (Miralles-Wilhelm, 2021).

Maintaining continuous soil cover is one of the core principles of conservation agriculture (CA), which not only reduces labor costs but also provides a range of ecosystem services (Crotty et al., 2019; Borelli, Panagos, 2020). Consequently, the use of cover crops (CC) is a vital solution contributing to sustainable soil and environmental management (Abdalla et al., 2019). The Soil Science Glossary (SSSA Glossary..., 2008) defines cover crops as a "close-growing crop that provides soil protection, seeding protection, and soil improvement between periods of normal crop production". Cover crops are cultivated not for harvest but to improve soil health and preserve biodiversity. They are sown during periods between main crops, when bare soil is exposed to erosion and nutrient loss (Eurostat, 2019; Panagos et al., 2015). Cover crops can be used as catch crops or green manure and can be classified into the following groups: legumes (e.g. alfalfa, vetches, clover), non-legumes (spinach, canola and flax), grasses (e.g. ryegrass and barley) and brassicas (e.g. radishes and turnips) (Abdalla et al., 2019). The positive impact of cover crops on soil health has been recognized since ancient times. Historical evidence suggests that cover crops were cultivated to improve soil fertility in China nearly 3,000 years ago (Pieters, 1927). Using cover crops is a nature-based solution that enhances soil structure throughout the soil profile, protects soil organic matter, and promotes nutrient cycling and biological activity in the soil (Lal, 2015). Soil quality indicators are essential for assessing soil condition. These indicators, derived from the physical, chemical, and biological properties of soil (Table 1), are crucial for evaluating changes resulting from various factors (Hobbs et al., 2008). Lal (2015) highlights that they are also valuable for monitoring the impact of ongoing climate change.

The literature provides numerous examples of the positive impact of cover crops on soil quality indicators. Studies by Wiesmeier (2015), Juan et al. (2017), Cerdà et al. (2022), Gao et al. (2022), Mrunalini et al. (2022), Quintarelli et al. (2022), and Schön et al. (2024) highlight their beneficial effects on bulk density, aggregate stability, water retention capacity, organic matter content, and microbial activity in the soil. Studies have also shown that ground cover plants reduce nutrient leaching, thereby protecting groundwater quality. Additionally, Dabney et al. (2011) and Halde et al. (2014) have demonstrated the positive influence of cover crop biomass on soil carbon sequestration processes.

Although the adoption of cover crops in European countries remains limited, growing environmental awareness and political support are driving a steady increase in their use (Borreli et al., 2020).

Several studies on cover crops (CC) have demonstrated that their effects on soil physical properties can vary depending on factors such as soil type, CC species, tillage systems, and climate. Additionally, while it is often assumed that improvements in soil chemical properties, such as increased soil organic carbon (SOC) content, positively influence soil physical and biological properties, these relationships have not been extensively explored in the literature. A comprehensive synthesis of research on the effects of CC on soil quality indicators is therefore crucial for understanding how CC influence the physical, chemical, and biological properties of soil. This study aims to review the literature to evaluate the impact of cover crops on selected soil quality properties, including bulk density, aggregate stability, water retention capacity, pH, organic matter and organic carbon content, nutrient availability, and biological activity. The findings of this review will provide valuable insights into the multifaceted role of CC in enhancing soil health and sustainability.

THE EFFECT OF COVER CROPS ON SOIL PHYSICAL PROPERTIES

Modern agriculture faces numerous challenges related to soil degradation, caused by intensified production, simplified crop rotations, and increased mechanization. Numerous scientific studies confirm the positive impact

Table 1. Potential soil benefits of cover crops in agricultural systems (Blanco-Canqui et al., 2015; Adetunji et al., 2020).

Physical	Chemical	Biological	Other
• Increase water infiltration into soil • Increase soil aggregate stability • Improve soil macroporosity • Increase residue cover • Reduce soil erosion • Reduce soil compaction • Reduce sudden fluctuations in soil temperature	• Increase soil organic carbon • Recycle nutrients • Increase N concentration	• Enhance microbial activity and biomass • Increase populations of earthworms and beneficial insects • Promote N fixation • Reduce some diseases	• Increase or sustain crop yields • Weed control • Potential forage harvest • Reduce labor costs • Reduced chemical costs • Improve landscape aesthetics

of cover crops on soil physical properties, such as bulk density, aggregate stability, and water retention capacity. Therefore, the use of cover crops is one of the tools for sustainable soil resource management (Snapp et al., 2005; Çerçioğlu et al., 2025)

The impact on soil bulk density

One of the fundamental problems in modern agriculture is the deterioration of arable soil quality due to excessive compaction. Determining bulk density is a method for assessing soil compaction and, consequently, its quality (Blanco-Canqui, 2020). This parameter defines the ratio of soil mass to its total volume and is an important physical property used to determine soil porosity and water characteristics. Information on bulk density is also utilized as an input parameter in models for water and nutrient transport. Moreover, bulk density is essential for accurate estimates of soil organic carbon stocks. Soils with high bulk density are characterized by reduced pore volume, which consequently limits the flow of water and air (Lal, Shukla, 2004). This leads to reduced availability of water and oxygen for plant roots, thereby negatively impacting their development and growth. Lower bulk density, apart from creating optimal conditions for plant development, positively influences the growth of microorganisms in the soil, thus promoting the formation of a stable soil structure (McKenzie, 1996).

Although most scientific studies indicate a positive effect of cover crops on soil bulk density (Breland, 1995; Terzoudi et al., 2007; Wiesmeier et al., 2015; Cerdà, 2018; Demir, Işık, 2019a; Demir et al., 2019; Cerdà et al., 2022), there are also studies in the literature that have shown no such effect (Sartori et al., 2022). The impact of cover crops on soil properties is complex and depends on many environmental factors such as seasonal changes in moisture and temperature, the type of cover crops used, and soil type (Hu et al., 2012). Studies conducted by Wiesmeier et al. (2015), Breland et al. (1995), Cerdà et al. (2022), and Sartori et al. (2022) demonstrated the positive effects of cover crops on soil microbial activity due to increased organic matter content (Blanco-Canqui et al., 2015). Microorganisms decomposing plant residues produce organic acids and polysaccharides, which promote the formation of stable macropores and soil aggregates. This process helps to reduce soil bulk density (Rorick, Kladivko, 2017; Koudahe et al., 2022). On the other hand, studies by Hubbard et al. (2013), Adeli et al. (2020) and Koudahe et al. (2022) emphasize that soil bulk density depends on the type of crop used. Research by Harasim et al. (2020) found that cover crops significantly modified this parameter. Mixed legume (*Vicia faba*, *V. sativa*) cultivation resulted in lower bulk density in the 5–10 cm soil layer (on average by 5%) compared to control plots without cover crops. The bulk density in the 15–20 cm soil layer was also lower in plots with cover crops compared to the control plots. A statistically significant reduction in bulk density was achieved with the cultivation of a mix of broad beans (*Vicia faba*) and common vetch (*Vicia sativa*) as well as lacy phacelia (*Phacelia tanacetifolia*). This effect occurs because plants with deep root systems, such as phacelia, loosen the soil structure, thereby increasing pore space (Villamil et al., 2006; Blanco-Canqui et al., 2015). As a result, soils demonstrate a greater capacity for water infiltration and storage as well as nutrient retention, which improves fertility and overall condition while promoting plant growth (Gentsch et al., 2024). In other studies conducted in Italy bulk density was measured at different depths and analyzed the impact of various tillage systems combined with cover crop cultivation, including oilseed radish (*Raphanus sativus*) and winter wheat (*Triticum aestivum*). In this case, cover crops did not significantly affect bulk density in any of the tested combinations. The lack of significant impact may be due to the short duration of cover crop cultivation (Sartori et al., 2022). Short-term use of cover crops may not induce substantial changes; however, as highlighted by Blanco-Canqui et al. (2011), long-term application of cover crop can mitigate soil compaction effects, particularly in the upper soil layers, thereby improving conditions for crop growth. The absence of effects may also be related to environmental conditions, soil type, and the type of cover crops used. For instance, in heavy clay soils, the roots of cover crops may struggle to penetrate, limiting their influence on soil structure. Therefore, the selection of cover crop species should be adapted to soil type. For light soils, species such as yellow lupine (*Lupinus luteus*), serradella (*Ornithopus sativus*), and phacelia are recommended. On medium-textured soils, sunflower (*Helianthus annuus*), narrow-leafed lupine (*Lupinus angustifolius*), rapeseed (*Brassica napus*), buckwheat (*Fagopyrum esculentum*), oilseed radish, and stubble turnip (*Brassica rapa*) are advised. For heavy soils, broad beans (*Vicia faba*) and common vetch are more suitable (Pikuła; https://www.tygodnik...). Gentsch et al. (2024) found that plants like rye and clover, with finer root systems, have a greater capacity for creating pore spaces in the soil, which in turn increases soil resistance to erosion. In contrast, Blanco-Canqui et al. (2015) observed that the deep roots of many cover crops, such as oilseed radish and alfalfa, loosen compacted soil, which is particularly significant in heavy soils such as clays and silts. The selection of cover crop species with appropriate root traits is therefore critical for improving soil health.

Moreover, under conditions of very intensive agricultural exploitation, the beneficial effects of cover crops can be counteracted by other farming practices (Sartori et al., 2022).

In conclusion, cover crops have the potential to reduce soil bulk density and improve its structure, especially with long-term use. In contrast, their short-term application, as well as specific soil and climatic conditions where other factors dominate their effectiveness, may limit their potential impact.

The impact on soil aggregate stability

Soil aggregates are the fundamental structural units of soil, formed during the decomposition of organic matter. In this process, microorganisms breaking down organic matter produce substances (mucus, polysaccharides, humic acids and proteins) that bind soil mineral particles, such as sand, silt, and clay, into larger structural units (Jouquet et al., 2006; Guhra et al., 2022). Structurally stable soil, with improved porosity, has a greater capacity for water absorption and retention, which increases its availability to plants while promoting air circulation, facilitating root respiration (Franzluebbers, 2002; An et al., 2010). Soil with stable aggregates is more resistant to disintegration caused by rainfall and surface runoff, reducing erosion risk. Furthermore, proper aggregation positively influences nutrient accumulation and microbial activity in soil (Sekaran et al., 2021). Soil structure is thus essential for both environmental protection and soil fertility (Obalum et al., 2013). As highlighted by authors, soil structure is critical to soil health and productivity, making the enhancement of aggregate stability an effective method for improving soil quality and addressing environmental issues resulting from soil degradation.

In recent decades, soil degradation has commonly been observed as a result of shifts in aggregate size distribution towards smaller aggregate classes, leading to reduction of their stability (Boix-Fayos et al., 2001). This degradation has been attributed to increased tillage intensity, monoculture practices, and mineral fertilization (Williams, Petticrew, 2009) which result in the loss of organic matter and deterioration of biological functions of the soil (Obalum et al., 2017). Restoring proper soil structure has therefore become a critical component of soil conservation strategies in sustainable agriculture (Williams, Petticrew, 2009; Lal, 2015; Obalum et al., 2017). The effect of cover crops on soil aggregate stability, particularly in the context of soil conservation, structural improvement, and increased erosion resistance, is a topic widely analyzed in scientific literature (Breland, 1995; Velykis et al., 2014; Wiesmeier et al., 2015; Cerdà et al., 2018; Garcia-Gonzalez et al., 2018; Harasim et al., 2020). Studies confirm that cover crops can be an effective tool for restoring healthy soil ecosystems (Williams, Petticrew, 2009; Lal, 2015; Obalum et al., 2017), which is crucial for sustainable soil management in the face of climate change (Six, Paustian, 2014).

The root systems of cover crops play a particularly important role in maintaining proper soil structure. Extensive and branched root systems penetrate deeply into the soil, creating a network that stabilizes soil structure. This process increases the soil's microporosity and macroporosity, improving its ability to infiltrate and retain water while also facilitating air circulation (Blanco-Canqui et al., 2015; Gentsch et al., 2024). Additionally, cover crop roots release organic substances, acting as a "natural glue" that binds soil particles, thereby enhancing their stability. These root secretions also positively influence the development of microorganisms (bacteria and fungi), which further strengthen aggregates by forming organic connections between soil particles. Moreover, the decomposition of root residues after the growth period of cover crops adds organic matter to the soil, improving its structure over the long term (Kavdir, Smucker, 2005).

The positive impact of root systems on aggregate stability was confirmed by Hudek et al. (2022). In a greenhouse experiment, the authors studied the effects of root traits of seven different cover crop species (oats, rye, buckwheat, vetch, radish, mustard, and phacelia) on improving soil physical properties. The authors emphasized that the positive impact on macroporosity and aggregate stability during cover crop growth depended on the morphology of the individual plant root systems. The results showed that total root length and root surface area strongly correlated with aggregate stability and soil macroporosity. Buckwheat, mustard, and rye increased aggregate stability and microporosity at the interface with the compacted layer by 10, 8, and 7%, respectively, compared to the bare soil control. Moreover, average root diameter negatively correlated with soil macroporosity, indicating that cover crops with finer root systems are more beneficial for pore formation than those with thicker taproots.

The impact on soil water retention

Climate change has increased the frequency of extreme weather events, such as drought, which has become a critical factor limiting agricultural production (Choat et al., 2012; Bu et al., 2018; Sun et al., 2020). In this context, the ability of soil to retain water is essential not only for plant survival during water scarcity but also for improving nutrient use efficiency by plants and reducing erosion. Thus, soil water retention is a crucial factor influencing agricultural production and the sustainable use of agricultural lands (Blanco-Canqui, Ruis, 2020).

Literature reports indicate that cover crops can serve as a nature-based solution to enhance soil water retention capacity (Franzluebbers, 2002; Thorup-Kristensen et al., 2003; Blanco-Canqui et al., 2015; Garcia-Gonzalez, 2018; Bacq-Labreuil et al., 2019). Cover crops can improve soil field capacity by enhancing soil structure. Their root systems create a network of channels in the soil, increasing porosity and allowing better water infiltration into deeper soil layers (Franzluebbers, 2002; Basche, DeLonge, 2017). This also reduces surface runoff and water erosion (Basche et al., 2016). Consequently, soil water balance is maintained, which is particularly beneficial in drought-prone regions (Lal, 2015; Blanco-Canqui, Ruis, 2020). Studies by Garcia-Gonzalez et al. (2018) demonstrated that using vetch and oats as cover crops increased soil field capacity in the 0–25 cm layer by 8% and 13%, respectively. Research by Haruna and Nkongolo (2015) and Bacq-Labreuil et al. (2019) showed that cover crops such as white mustard and lacy phacelia significantly increased soil moisture in the topsoil layers (0–10 cm), which is particularly beneficial for cereal crops. Similarly, in experiments by Harasim et al. (2020), white mustard significantly increased soil moisture content (in volumetric terms) in the 5–10 cm layer compared to control plots. Other cover crops, such as oats and phacelia, caused only minor increases in soil moisture in the 5–10 cm layer. Additionally, crops like rye and oats were found to promote a more uniform distribution of water within the soil profile (Kaspar, Singer, 2011). Wang et al. (2015) emphasized that cover crops, particularly those with deep root systems, are capable of retaining water over extended periods. Other studies by Thorup-Kristensen et al. (2003) showed that introducing cover crops can significantly increase soil organic matter content. Elevated organic matter levels reduce the risk of soil drying, which is particularly important for light, permeable soils (Jiang et al., 2020). Harasim et al. (2020) also observed that leaving cover crop residues on the field as mulch increased soil moisture by reducing surface runoff, enhancing infiltration, and decreasing evaporation. In a study conducted in Serbia, Krstić et al. (2018) demonstrated that the cultivation of cover crops can lead to reduced soil moisture content during the spring period. In this research, cover crops such as common vetch (*Vicia sativa*) and triticale (× *Triticosecale*) decreased water availability for silage maize, which negatively affected its yield. The authors suggest that under conditions of limited precipitation, cover crops may compete with main crops for water resources, potentially leading to yield reductions.

In conclusion, the use of cover crops is an effective method for improving soil water retention, which is particularly relevant in the context of climate change and the need for sustainable water resource management in agriculture.

THE EFFECT OF COVER CROPS ON SOIL CHEMICAL PROPERTIES

Soil chemical properties play an important role in shaping soil fertility, which is a fundamental determinant of productivity. In the face of increasing soil degradation caused by the intensification of agricultural practices, the use of cover crops is one management strategy that, through their beneficial effects on soil chemical properties, contributes to soil restoration and maintenance of soil health.

The impact on soil pH

One of the primary indicators of soil quality that influences its productivity is pH (Havlin et al., 2014). Literature data indicate that pH affects the physical, chemical, and biological properties of soil. It influences soil structure through its effect on soil colloids and aggregates. In acidic soils, dominated by H^+ and Al^{3+} ions, aggregates tend to break down (Oades, 1984). Soils with excessively low pH also exhibit reduced phosphorus availability to plants, as phosphorus forms insoluble compounds with aluminum and iron. Also in alkaline soils, phosphorus binds with calcium, similarly becoming less available (Penn, Camberato, 2019). Additionally, pH affects the conditions for soil microorganisms involved in organic matter decomposition. Soil Acidification may limit bacterial activity, altering microbial balance and influencing biogeochemical processes (Rousk et al., 2010).

Cover crops play an important role in soil quality management, including shaping its pH. However, this impact varies and depends on many factors, including the species of cover crops (Feng et al., 2021). In research conducted by Demir (2020), in which cover crop treatments significantly reduced soil pH from 7.48 (in the control plot) to 6.92 for hairy vetch (*Vicia villosa*) at a depth of 0–20 cm, and from 7.46 (control) to 6.90 in the case of white clover (*Trifolium repens* L.), also at a depth of 0–20 cm. Similarly, the use of cover crops significantly decreased soil pH (Demir, Işık, 2019b; Demir, Işık, 2019c; Demir et al., 2019), which has been attributed to the presence of acidic root exudates that may affect the availability of nutrients in the rhizosphere. According to information available in the literature, acidification of soil by cover crops usually results from an imbalance between the carbon and nitrogen cycles (Vanzolini et al., 2017). Additionally, the uptake of cations and anions by plants from the soil solution to meet growth demands alters ionic equilibrium. In most cases, plants absorb more cations than anions, leading to the release of protons into the soil to maintain charge balance. Furthermore, during the biological fixation of atmospheric nitrogen (N_2) by legumes, proton excretion by roots is associated with the accumulation of organic anions in plant tissues. The decomposition of these anions by soil microorganisms can lead to an decrease in soil pH. Some authors suggest that soil acidification may also result from the accumulation of fresh organic matter (Mengel, Steffens, 1982). The decomposition of plant residues from species producing large biomass quantities, such as rye or rapeseed, releases organic acids, which lower soil pH (Gentsch et al., 2024). Conversely, the incorporation of residues from cover crops like buckwheat, characterized by a high calcium content in their tissues, can neutralize or raise soil pH (Khan et al., 2021).

The impact on soil organic matter

Soil organic matter (SOM) is a critical component for maintaining soil health. It influences various physical, chemical, and biological soil properties, such as structure, compaction, sorption capacity, nutrient availability for plants, pH, and microbial activity, all of which directly affect crop yields (Dexter, 2004; Van Groenigen et al., 2017). SOM has a high water-holding capacity, which is particularly important during drought periods. Additionally, SOM contributes to mitigating climate change by reducing carbon dioxide emissions into the atmosphere (Thorup-Kristensen et al., 2003).

The incorporation of cover crop biomass into the soil is an effective method for enhancing SOM in the long term (Lu et al., 2000). Cover crops supply fresh organic matter to the soil through the decomposition of root biomass and aboveground plant parts. These effects are often compared to the fertilizing effects of manure, with the impact of cover crop biomass on soil properties potentially lasting for several years (Reddy et al., 2003; Sarrantonio, Gallandt, 2003). Studies have shown that different cover crop species, such as rye and clover, can increase soil organic carbon (SOC) levels by stimulating microbial and fungal activity in the soil (Khan et al., 2021; Feng et al., 2021). The biomass serves as a substrate for microorganisms, which convert it into stable forms of organic carbon. Increased SOC content due to cover crop use has also been observed in studies by Demir et al., (2019); Ding et al. (2006), and Köpke, Nemecek (2010), Ramos et al. (2018), Cerdà et al. (2022). For instance, Demir et al. (2019) demonstrated that the application of hairy vetch (*Vicia villosa*) and Hungarian vetch (*Vicia pannonica*) increased the soil organic matter (SOM) content in clay soil from 14.9 g kg^{-1} to 24.4 g kg^{-1} in an apricot orchard located in the Malatya Province of Türkiye. In a study conducted in Spain, the use of vetch and oats as cover crops increased SOC content from 5.4 g kg^{-1} (in bare soil) to 8.4 g kg^{-1} and 9 g kg^{-1}, respectively (Ramos et al., 2018). Similarly, Cerdà et al. (2022) confirmed these findings, highlighting the effectiveness of vetch and oats in enhancing SOM. The impact of broad beans as a cover crop on SOM was discussed by Köpke and Nemecek (2010), who emphasized that broad bean residues, rich in nitrogen, enrich SOM upon decomposition, improving soil structure and fertility. Incorporating broad beans into crop rotations contributes to long-term SOM increases, positively impacting soil productivity. Positive outcomes of cover crop use were also reported in studies conducted on degraded soils in Moldova. The application of a mix of hairy vetch and winter wheat increased SOC in the topsoil layer from 11.3 to 11.6 kg m^{-2} in experiments located in Orhei and from 10.2 to 10.5 kg m^{-2} in experiments in Cahul. Researchers noted that using this mix as a cover crop and green manure resulted in carbon sequestration of 3 t C ha^{-1} yr^{-1}, indicating the potential of cover crops to mitigate climate change (Wiesmeier et al., 2015). In contrast, studies by Yang et al. (2004) and Abdollahi and Munkholm (2014) showed no significant changes in organic matter content after the application of cover crops.

By increasing soil organic matter content, improving soil fertility and structure, and enhancing nutrient availability, cover crops contribute to higher yields in subsequent crops. Cover crop cultivation is an environmentally friendly practice that provides numerous benefits for both soil and agriculture.

The impact on soil nitrogen and phosphorus content

Nitrogen (N) and phosphorus (P) are essential nutrients for plant growth and development, but their excessive use in intensive agriculture often leads to environmental degradation. The leaching of nitrogen and phosphorus from soils into groundwater and surface waters contributes to eutrophication, resulting in reduced biodiversity and impaired ecosystem functioning (Carpenter et al., 1998). Effective retention of these nutrients in the soil is therefore critical both for environmental protection and for improving soil fertility.

One effective strategy for nutrient retention is the implementation of appropriate agricultural practices. Cover crops play a significant role in nitrogen retention, particularly during fallow periods when the risk of nutrient leaching is high (Sapkota et al., 2012). They act as buffers, providing an effective solution to prevent nutrient loss (Askegaard, Eriksen, 2008). As such, they are considered an important element of sustainable agriculture. Cover crops are especially valued by organic farmers, who often use them as green manures to enhance nitrogen availability for subsequent crops (Komainda et al., 2016). By accumulating nitrogen in both aboveground and belowground biomass, cover crops reduce nutrient losses, thereby minimizing groundwater and surface water pollution (Tonitto et al., 2006; Cerdà et al., 2022). Leguminous cover crops, such as vetch and clover, are particularly noteworthy as they fix atmospheric nitrogen through symbiosis with rhizobia. After the growing cycle, the nitrogen accumulated in the biomass is released into the soil, increasing its availability for subsequent crops (Thorup-Kristensen et al., 2003). This was confirmed by Wiesmeier et al. (2015) in their studies on degraded steppe soils in Moldova. Their experiments demonstrated that hairy vetch (*Vicia villosa*), used as green manure, significantly enriched the soil with nitrogen. This effect was attributed to the ability of hairy vetch to fix atmospheric nitrogen, with up to 80% of the nitrogen introduced into the soil originating from this process. The increased nitrogen content improved soil fertility, leading to higher yields of subsequent crops: sunflower yields increased by 22% in Orhei, and maize yields by 18% in Cahul. In Poland, studies conducted by the Małopolska Agricultural Advisory Center in Karniowice found that the use of vetch as a cover crop in zucchini and tomato cultivation under covers supplied 252 kg N ha^{-1}. Pea crops provided 155 N ha^{-1}, while mixtures of vetch with rye and peas with oats accumulated 173 kg N ha^{-1} and 136 kg N ha^{-1} of organic nitrogen, respectively (Domagała-Świątkiewicz, Siwek; https://modr.pl/technologie...). Long-term field experiments in France by Constantin et al. (2010) evaluated various agricultural practices in terms of their impact on nitrogen balance and nitrate leaching. These studies confirmed that cover crops effectively reduced nitrate losses, contributing to improved nitrogen management in agricultural systems.

Phosphorus losses, on the other hand, are primarily caused by surface runoff and soil erosion. Cover crops, with their extensive root systems, improve soil structure, which aids in phosphorus retention and its efficient use by cash crops. The decomposition of cover crop biomass gradually releases phosphorus over time, integrating it into the nutrient cycle (Sarrantonio, Gallandt, 2003). Sartori et al. (2022) found that in conservation agriculture systems that combine the use of cover crops with reduced tillage intensity, phosphorus is retained more effectively in the soil. This improves the overall phosphorus balance in the soil and minimizes its losses to the environment, contributing to the protection of surface water quality.

THE EFFECT OF COVER CROPS ON SOIL BIOLOGICAL PROPERTIES

Soil microorganisms play an important role in the functioning of agricultural ecosystems, thereby influencing organic matter cycling, nutrient availability and soil structure. Their enzymatic activity, an indicator of the biological quality of the soil, is strongly dependent on agricultural practices. In recent years, increasing attention has been paid to the impact of cover crops on soil microbial diversity and activity as part of a sustainable agriculture strategy.

The impact on soil microbial activity

Soil microorganisms are an integral component of a healthy soil ecosystem. Their diversity and activity are essential for soil fertility, plant growth, and environmental protection. Microorganisms contribute to the decomposition of organic matter, the formation of soil aggregates, nutrient availability for plants, and protection against pathogens. The interaction between microorganisms and higher plants maintains equilibrium in soil environments, and any changes in the physical and chemical properties of the soil can disrupt this balance (Hayat et al., 2010; Wang et al., 2024).

The level of enzymatic activity in the soil, particularly dehydrogenase activity, provides insights into the soil environment and serves as an indicator of its fertility and productivity. Factors such as soil pH, water-air relations, and organic matter content—shaped by farming systems and the type of fertilizers applied—play a crucial role in determining microbial populations and enzymatic activity in the soil. Supporting microbial biodiversity through sustainable agricultural practices is essential for the long-term productivity and health of soils (Bielińska, Mocek, 2003).

Although relatively few studies in Europe have investigated the effects of cover crops on microbial biodiversity, existing data indicate that sustainable farming practices, including the use of cover crops, play a significant role in ensuring the long-term productivity and health of soils. Research suggests that cover crops can substantially influence the diversity and activity of soil microorganisms, thereby enhancing soil quality. Cerdà et al. (2022) demonstrated that the use of vetch and oats as cover crops increased microbial and fungal activity, which positively affected soil organic carbon content. Cover crops enrich soils with organic matter, supporting nutrient cycling, particularly nitrogen, which, in turn, enhances microbial activity (Quintarelli et al., 2022; Schön et al., 2024). In a study conducted by Harasim et al. (2020), it was demonstrated that the use of white mustard (*Sinapis alba*) as a catch crop significantly increased the activity of dehydrogenase and urease enzymes in various soil layers. The control treatments (without a catch crop) exhibited the lowest enzymatic activity, both in the 5–10 cm and 15–20 cm soil layers. In turn, research by Pięta and Kęsik (2006) conducted in Poland revealed that the cultivation of spring rye (*Secale cereale*) and common vetch (*Vicia sativa*) as cover crops may lead to an increased presence of soil-borne pathogenic fungi, including *Fusarium culmorum*, *F. oxysporum*, *F. solani*, *Penicillium verrucosum*, and *Pythium irregulare*. These pathogens contributed to poor emergence and compromised seedling health of onion (*Allium cepa*).

SUMMARY

The review of the available literature confirms that the use of cover crops is an effective strategy for supporting sustainable soil management, simultaneously contributing to improved soil health and productivity. Cover crops have a positive impact on the physical, chemical, and biological properties of soil. They reduce bulk density, enhance soil aggregate stability, and increase the soil's water retention capacity, which is crucial in mitigating the effects of climate change, such as droughts. Additionally, cover crops positively influence the chemical properties of soil by enriching it with organic matter, improving soil organic carbon content, and regulating pH. Through their extensive root systems, cover crops enhance the availability and retention of nutrients such as nitrogen and phosphorus, reducing their losses to the environment and protecting the quality of groundwater and surface waters. An important aspect is the impact of cover crops on the biological properties of soil, including increased activity of microorganisms and enzymes such as dehydrogenase and urease. Cover crops enrich the soil with organic matter, supporting the development and activity of microorganisms, which promotes nutrient cycling and improves soil fertility. Thus, cover crops can be an important component of sustainable agriculture, aiding adaptation to changing climatic and environmental conditions.

REFERENCES

Abdalla M., Hastings A., Cheng K., Yue Q., Chadwick D., Espenberg M., Truu J., Rees R.M., Smith P., 2019. A critical review of the impacts of cover crops on nitrogen leaching, net greenhouse gas balance and crop productivity. Global Change Biology, 25: 2530-2543, https://doi. org/10.1111/gcb.14644. .

Abdollahi L., Munkholm L.J., 2014. Tillage system and cover crop effects on soil quality: I. Chemical, mechanical, and biological properties. Soil Science Society of America Journal, 78: 262-270, https://doi.org/10.2136/sssaj2013.07.0301.

Adeli S., Blanco-Canqui H., Mikha M.M., Presley D.R., Claassen M.M., 2020. Improving soil physical properties through the use of cover crops: A review. Agrosystems, Geosciences & Environment, 3(1), e20070. https://doi.org/10.1002/agg2.20070.

Adetunji A.T., Ncube B., Mulidzi R., Lewu F.B., 2020. Management impact and benefit of cover crops on soil quality: a review. Soil and Tillage Research, 204, 104717, https://doi.org/10.1016/j.still.2020.104717.

An S., Mentler A., Mayer H., Blum W.E.H., Elsenbeer H., 2010. Soil aggregation, aggregate stability, organic carbon and nitrogen in different soil aggregate fractions under forest, shrub and pasture ecosystems in southern Ecuador. Soil Science, 81(3): 226-233, doi: 10.1016/j.catena.2010.04.002

Askegaard M., Eriksen J., 2008. Residual effect and leaching of N and K in cropping systems with clover and ryegrass catch crops on a coarse sand. Agriculture, Ecosystems & Environment, 123: 99-108.

Bacq-Labreuil A., Crawford J., Mooney S.J., Neal A.L., Ritz K., 2019. Phacelia (Phacelia tanacetifolia Benth.) affects soil structure differently depending on soil texture. Plant and Soil, 441: 543-554.

Basche A.D., DeLonge M.S., 2017. The impact of continuous living cover on soil hydrologic properties: A meta-analysis. Soil Science Society of America Journal, 81(5): 1179-1190, https://doi.org/10.2136/sssaj2017.03.0077.

Basche A.D., Kaspar T.C., Archontoulis S.V., Jaynes D.B., Parkin T.B., Miguez F.E., 2016. Soil water improvements with the long-term use of a winter rye cover crop. Agriculture, Ecosystems & Environment, 221: 103-111, https://doi.org/10.1016/j.agee.2016.01.014.

Bielińska E.J., Mocek A., 2003. Aktywność enzymatyczna gleby użytkowanej sadowniczo jako wskaźnik stanu środowiska wywołany stosowaniem ściółek z tworzyw sztucznych. Zeszyty Problemowe Postępów Nauk Rolniczych, 492: 25-37.

Blanco-Canqui H., Mikha M.M., Presley D.R., Claassen M.M., 2011. Addition of Cover Crops Enhances No-Till Potential for Improving Soil Physical Properties Soil Science Society of America Journal, 75: 1471-1482, https://doi.org/10.2136/sssaj2010.0430.

Blanco-Canqui H., Shaver T.M., Lindquist J.L., Shapiro C.A., Elmore R.W., Francis C.A., Hergert G.W., 2015. Cover crops and ecosystem services: Insights from studies in temperate soils. Agronomy Journal, 107(6): 2449-2474.

Blanco-Canqui H., Ruis S.J., 2020. Cover crop impacts on soil physical properties: A review. Soil Science Society of America Journal. 84: 1527-1576, https://doi.org/10.1002/saj2.20129, 2020.

Breland T.A., 1995. Green manuring with clover and ryegrass catch crops undersown in spring wheat: Effects on soil structure. Soil Use & Management, 11: 163-167.

Borrelli P., Panagos P., 2020. An indicator to reflect the mitigating effect of Common Agricultural Policy on soil erosion. Land Use Policy, 92, 104467.

Boix-Fayos C., Calvo-Cases A., Imeson A.C., Soriano-Soto M.D., 2001. Influence of soil properties on the aggregation of some Mediterranean soils and the use of aggregate size and stability as land degradation indicators. Catena, 44(1): 47-67, https://doi.org/10.1016/S0341-8162(00)00176-4.

Bu X., Gu X., Zhou X., Zhang M., Guo Z., Zhang J., Zhou I., Chen X., Wang X., 2018. Extreme drought slightly decreased soil labile organic C and N contents and altered microbial community structure in a subtropical evergreen forest. Forest Ecology and Management, 429: 18-27.

Carpenter S.R., Caraco N.F., Correll D.L., Howarth R.W., Sharpley A.N., Smith V.H., 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications, 8(3): 559-568, https://doi.org/10.1890/1051-0761(1998)008[0559:NPOSWW]2.0.CO;2.

Çerçioğlu M., Udawatta R.P., Anderson S.H., 2025. Use of cover crops for sustainable management of soil condition and health: A review. Soil Security, 13, 100177, https://doi.org/10.1016/j.soisec.2025.100177.

Cerdà A., Rodrigo-Comino J., Giménez-Morera A., Keesstra S.D., 2018. Hydrological and erosional impact and farmer's perception on catch crops and weeds in citrus organic farming in Canyoles river watershed, Eastern Spain. Agriculture, Ecosystems & Environment, 258: 49-58, https://doi.org/10.1016/j.agee.2018.02.015.

Cerdà A., Franch-Pardo I., Novara A., Sannigrahi S., Rodrigo-Comino J., 2022. Examining the Effectiveness of Catch Crops as a Nature-Based Solution to Mitigate Surface Soil and Water Losses as an Environmental Regional Concern. Earth Systems and Environment, 6(1), https://doi.org/10.1007/s41748-021-00284-9.

Choat B., Jansen S., Brodribb T.J., Cochard H., Delzon S., Bhaskar R., et al., 2012. Global convergence in the vulnerability of forests to drought. Nature, 29, 491(7426): 752-755.

Constantin J., Mary B., Laurent F., Aubrion G., Fontaine A., Kerveillant P., Beaudoin N., 2010. Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. Agriculture, Ecosystems & Environment, 135: 268-278, 10.1016/j.agee.2009.10.005.

Crotty F.V., Fychan R., Sanderson R., Rhymes J.R., Bourdin F., Scullion J., 2019. Arable soil quality impacts of organic farming systems established for 5–10 years in England. Journal of Agricultural Science, 157(5): 674-684, https://doi.org/10.1017/S0021859619000452.

Dabney S.M., Delgado J.A., Meisinger J.J., Schomberg H.H., Liebig M.A., Kaspar T., Reeves W., 2011. Using cover crops and cropping systems for nitrogen management. pp. 230-281. In: Advances in nitrogen management for water quality; Eds.: J.A. Delgado & R.F. Follet, Ankeny, IA: Soil and Water Conservation Society.

Demir Z., 2020. The evaluation of basal respiration and some chemical properties of soils under cover crop treatments in a cherry orchard. European Journal of Soil Science, 9: 151-164, https://doi.org/10.18393/ejss.706686.

Demir Z., Isik D., 2019a. Effects of cover crops on soil hydraulic properties and yield in a persimmon orchard. Bragantia 78: 596-605, https://doi.org/10.1590/1678- 4499.2010197.

Demir Z., Işık, D., 2019b. Comparison of Different Cover Crops on DTPA-Extractable Micronutrients in Hazelnut and Apple Orchards. Turkish Journal of Agricultural and Natural Sciences, 6(2): 137-147, https://doi.org/10.30910/turkjans.556592.

Demir Z., Işık D., 2019c. The comparative effects of different cover crops on DTPA-extractable micronutrients in orchards with loam and clay textured soils. Journal of Agricultural Faculty of Gaziosmanpasa University, 36(2): 107-116.

Demir Z., Tursun N., Isik D., 2019. Effects of different cover crops on soil quality parameters and yield in apricot orchard. International Journal of Agriculture and Biology, 21: 399-408, https://doi. org/10.17957/IJAB/15.0000.

Dexter A.R., 2004. Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter. Geoderma, 120(3-4): 201-214, doi:10.1016/j.geoderma.2003.09.004.

Ding G., Liu X., Herbert S., Novak J., Amarasiriwardena D., Xing B., 2006. Effect of Cover Crop Management on Soil Organic Matter. Geoderma, 130(3-4): 229-239.

Domagała-Świątkiewicz I., Siwek P. Rośliny okrywowe w ekologicznej uprawie warzyw w tunelach foliowych. https://modr.pl/technologie-ekologicznej-produkcji-ogrodniczej/strona/rosliny-okrywowe-w-ekologicznej-uprawie-warzyw (last access: 9 September 2025)

Eurostat, 2019. Glossary: Arable land covered with cover crop or intermediate crop. Retrieved February 4, from https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Arable_land_covered_with_cover_crop_or_intermediate_crop. (last access: 31 October 2024)

Feng H., Sekaran U., Wang T., Kumar S., 2021. On-farm assessment of cover cropping effects on soil C and N pools, enzyme activities, and microbial community structure. The Journal of Agricultural Science, 159(3-4): 216-226, doi:10.1017/s002185962100040x.

Franzluebbers A.J., 2002. Water infiltration and soil structure related to organic matter and its stratification with depth. Soil and Tillage Research, 66(2): 197-205, https://doi.org/10.1016/S0167-1987(02)00027-2.

Garcia-Gonzalez I., Hontoria C., Gabriel J.L., Alonso-Ayuso M., Quemada M., 2018. Cover crops to mitigate soil degradation and enhance soil functionality in irrigated land. Geoderma, 322: 81-88.

Gao H., Tian G., Khashi u Rahman M., Wu F., 2022. Cover Crop Species Composition Alters the Soil Bacterial Community in a Continuous Pepper Cropping System. Frontiers in Microbiology, 12:789034, doi: 10.3389/fmicb.2021.789034.

Gentsch N., Riechers F.L., Boy J., Schweneker D., Feuerstein U., Heuermann D., Guggenberger G., 2024. Cover crops improve soil structure and change organic carbon distribution in macroaggregate fractions. SOIL, 10: 139-150, https://doi.org/10.5194/soil-10-139-2024.

Guhra T., Stolze K., Rillig M.C., 2022. Pathways of biogenically excreted organic matter into soil aggregates. Soil Biology and Biochemistry, 164(3): 108483, doi: 10.1016/j.soilbio.2021.108483.

Halde C., Gulden R.H., Entz M.H., 2014. Selecting cover crop mulches for organic rotational no-till systems in Manitoba, Canada. Agronomy Journal, 106: 1193-1204, https://doi.org/10.2134/agron j13.0402.

Harasim E., Antonkiewicz J., Kwiatkowski C.A., 2020. The Effects of Catch Crops and Tillage Systems on Selected Physical Properties and Enzymatic Activity of Loess Soil in a Spring Wheat Monoculture. Agronomy. 10, 334, https://doi.org/10.3390/agronomy10030334.

Haruna S.I., Nkongolo N.V., 2015. Cover crop management effects on soil physical and biological properties. Procedia Environmental Sciences, 29: 13-14.

Hayat R., Ali S., Amara U., et al., 2010. Soil beneficial bacteria and their role in plant growth promotion: a review. Annals of Microbiology, 60: 579-598, https://doi.org/10.1007/s13213-010-0117-1.

Havlin J.L., Beaton J.D., Tisdale S.L., Nelson W.L., 2014. Soil Fertility and Fertilizers; An Introduction to Nutrient Management. 6th Edition, Prentice Hall, Upper Saddle River, NJ.

https://agriculture.ec.europa.eu/sustainability/environmental-sustainability/natural-resources/soil_en (last access: 31 October 2024).

Hobbs P.R., Sayre K., Gupta R., 2008. The role of conservation agriculture in sustainable agriculture, Philosophical Transactions of the Royal Society B, 363: 543-555, https://doi.org/10.1098/rstb.2007.2169.

Hu W., Shao M.A., Si B.C., 2012. Seasonal changes in surface bulk density and saturated hydraulic conductivity of natural landscapes. European Journal of Soil Science, 63: 820-830, https://doi.org/10.1111/J.1365-2389.2012.01479.X, 2012.

Hubbard R.K., Strickland T.C., Phatak S.C., 2013. Effects of cover crop systems on soil physical properties and carbon/nitrogen relationships in the coastalplain of southeastern USA. Soil and Tillage Research, 126, 276e283.

Hudek C., Putinica C., Otten W., De Baets S., 2022. Functional root trait-based classification of cover crops to improve soil physical properties. European Journal of Soil Science, 73, e13147, https://doi.org/10.1111/ejss.13147.

Jouquet P., Dauber J., Lagerlöf J., Lavelle P., Lepage M., 2006. Soil invertebrates as ecosystem engineers: Intended and accidental effects on soil and feedback loops. Applied Soil Ecology, 32(2): 153-164, https://doi.org/10.1016/j.apsoil.2005.07.004.

Jiang Y., Zeng Z., Lyu X., 2020. Effect of cover crops on soil properties and microbial communities. Journal of Soil and Water Conservation, 75(3): 351-359.

Kaspar T.C., Singer J.W., 2011. The use of cover crops to manage soil. Soil Management and Conservation, 1: 321-338.

Kavdır Y., Smucker A.J.M., 2005. Soil aggregate sequestration of cover crop root and shoot-derived nitrogen. Plant and Soil, 272: 263-276, https://doi.org/10.1007/s11104-004-5294-x.

Khan R., Farooque A.A., Brown H.C.P., Zaman Q.U., Acharya B., Abbas F., McKenzie-Gopsill A., 2021. The Role of Cover Crop Types and Residue Incorporation in Improving Soil Chemical Properties. Agronomy. 11, 2091, https://doi.org/10.3390/agronomy11102091.

Komainda M., Taube F., Kluß C., Herrmann A., 2016. Above- and belowground nitrogen uptake of winter catch crops sown after silage maize as affected by sowing date European Journal of Agronomy, 79: 31-42, doi: 10.1016/j.eja.2016.05.007.

Köpke U., Nemecek T., 2010. Ecological services of faba bean. Field Crops Research, 115(3): 217-233, https://doi.org/10.1016/j.fcr.2009.10.012.

Koudahe K., Allen S.C., Djaman K., 2022. Critical review of the impact of cover crops on soil properties. International Soil and Water Conservation Research, 10(3): 343-354, https://doi.org/10.1016/j.iswcr.2022.03.003.

Krstić Đ., Vujić S., Jaćimović G., D'Ottavio P., Radanović Z., Erić P., Ćupina B., 2018. The Effect of Cover Crops on Soil Water Balance in Rain-Fed Conditions. Atmosphere. 9, 492, https://doi.org/10.3390/atmos9120492.

Lal R., 2015. Restoring Soil Quality to Mitigate Soil Degradation. Sustainability, 7: 5875-5895, https://doi.org/10.3390/su7055875.

Lal R., Shukla M.K., 2004. Principles of Soil Physics. New York: Marcel Dekker.

Lu Y.C., Watkins K.B., Teasdale J.R., Abdul-Baki A.A., 2000. Cover Crops in Sustainable Food Production. Food Reviews International, 16: 121-157.

McKenzie D.K., 1996. Soil structure and plant growth: Impact of bulk density and biopores. Plant and Soil, 185: 151-162, https://doi.org/10.1007/BF02257571.

Mengel K., Steffens D., 1982. Relationship between cation/anion uptake of red clover and release of protons by the roots. Zeitschrift für Pflanzenernährung und Bodenkunde, 145: 229-236.

Miralles-Wilhelm F., 2021. Nature-based solutions in agriculture – Sustainable management and conservation of land, water, and biodiversity. Virginia. FAO and The Nature Conservancy, https://doi.org/10.4060/cb3140en.

Mrunalini K., Behera B., Jayaraman S., Abhilash P.C., Dubey P.K., Swamy G.N., Prasad J.V.N.S., Rao K.V., Krishnan P., Pratibha G., Srinivasa Rao C., 2022. Nature-based solutions in soil restoration for improving agricultural productivity. Land Degradation and Development, 33(8), https://doi.org/10.1002/ldr.4207.

Oades J.M., 1984. Soil organic matter and structural stability: mechanisms and implications for management. Plant and Soil, 76(1-3): 319-337.

Obalum S.E., Chibuike G.U., Peth S., Ouyang Y., 2017. Soil organic matter as sole indicator of soil degradation. Environmental Monitoring and Assessment, 189, 176, https://doi.org/10.1007/s10661-017-5881-y.

Obalum S.E., Watanabe Y., Igwe C.A., Obi M.E., Wakatsuki T., 2013. Improving on the Prediction of Cation Exchange Capacity for Highly Weathered and Structurally Contrasting Tropical Soils from Their Fine-Earth Fractions. Communications in Soil Science and Plant Analysis, 44(12): 1831-1848, https://doi.org/10.1080/00103624.2013.790401.

Panagos P., Borrelli P., Meusburger K., Alewell C., Lugato E., Montanarella L., 2015. Estimating the soil erosion cover-management factor at the European scale. Land use policy, 48: 38-50, doi: 10.1016/j. landusepol.2015.05.021.

Penn C.J., Camberato J.J., 2019. A Critical Review on Soil Chemical Processes that Control How Soil pH Affects Phosphorus Availability to Plants. Agriculture, 9(6), 120, https://doi.org/10.3390/agriculture9060120.

Pieters A.J., 1927. Green manuring principles and practices. John Wiley & Sons, Inc., New York, NY, 267 pp.

Pięta D., Kęsik T., 2006. Pathogenic soilborne fungi of onion cultivated after cover crops: spring rye and common vetch. Acta Scientiarum Polonorum. Hortorum Cultus, 5(1): 71-78.

Pikuła D. Międzyplony pozwalają zachować wodę w glebie i podwyższyć plon z uprawy głównej. https://www.tygodnik-rolniczy.pl/uprawa/agrotechnika/miedzyplony-pozwalaja-zachowac-wode-w-glebie-i-podwyzszyc-plon-z-uprawy-glownej-2503163 (last access: 9 september 2025)

Quintarelli V., Radicetti E., Allevato E., Stazi S.R., Haider G., Abideen Z., Bibi S., Jamal A., Mancinelli R., 2022. Cover Crops for Sustainable Cropping Systems: A Review. Agriculture 12(12), 2076, https://doi.org/10.3390/agriculture12122076.

Ramos F.T., Dores E.F.D.C., Weber O.L.D.S., Beber D.C., Campelo J.H. Jr., Maia J.C.D.S., 2018. Soil organic matter doubles the cation exchange capacity of tropical soil under no-till farming in Brazil. Journal of the Science of Food and Agriculture, 98: 3595-3602, doi: 10.1002/jsfa.8881.

Reddy K.N., Zablotowicz R.M., Locke M.A., Koger C.H., 2003. Cover crop, tillage, and herbicide effects on weeds, soil properties, microbial populations, and soybean yield. Weed Science, 5: 987-994, doi:10.1614/p2002-169.

Rorick J.D., Kladivko E.J., 2017. Cereal rye cover crop effects on soil carbon and physical properties in southeastern Indiana. Journal of Soil and Water Conservation, 72(3), 260e265.

Rousk J., Bååth E., Brookes P.C., Lauber C.L., Lozupone C., Caporaso J.G., Knight R., Fierer N., 2010. Soil bacterial and fungal communities across a pH gradient in an arable soil. International Society for Microbial Ecology, 4(10): 1340-1351, doi: 10.1038/ismej.2010.58.

Sapkota T.B., Askegaard M., Laegdsmand M., Olesen J.E., 2012. Effects of catch crop type and root depth on nitrogen leaching and yield of spring barley. Field Crops Research 125: 129-138, https://doi.org/ 10.1016/j.fcr.2011.09.009.

Sarrantonio M., Gallandt E., 2003. The Role of Cover Crops in North American Cropping Systems. Journal of Crop Production, 8(1-2): 53-74, https://doi.org/10.1300/J144v08n01_04.

Sartori F., Piccoli I., Polese R., Berti A., 2022. Transition to conservation agriculture: how tillage intensity and covering affect soil physical parameters. SOIL, 8: 213-222, https://doi.org/10.5194/soil-8-213-2022.

Schön J., Gentsch N., Breunig P., 2024. Cover crops support the climate change mitigation potential of agroecosystems. PLOS One, https://doi.org/10.1371/journal.pone.0302139

Sekaran U., Sagar K.L., Kumar S., 2021. Soil aggregates, aggregate-associated carbon and nitrogen, and water retention as influenced by short and long-term no-till systems. Geoderma, 104885, https://doi.org/10.1016/j.still.2020.104885.

Six J., Paustian K., 2014. Aggregate-associated soil organic matter as an ecosystem property and a measurement tool. Soil Biology and Biochemistry, 68: A4–A9, https://doi.org/10.1016/j.soilbio.2013.06.014.

Snapp S., Swinton S.M., Labarta R., Mutch D.,. Black J.R, Leep R., Nyiraneza J., O'Neil K., 2005. Evaluating cover crops for benefits, costs, and performance within cropping system niches. Agronomy Journal, 97: 322-332, https://doi.org/10.2134/agronj2005.0322a.

SSSA Glossary of Soil Science Terms, 2008. Soil Science Glossary Terms Committee; Soil Science Society of America; Google Books; ASA-CSSA-SSSA: Madison, WI, USA, 2008.

Sonneveld B.G.J.S., Merbis M.D., Alfarra A., Ünver I.H.O., Arnal M.F., 2018. Food and Agriculture Organization of the United Nations. Nature-based solutions for agricultural water management and food security, ISBN 978-92-5-131125-7, 57 pp.

Sun Y., Chen H.Y.H., Jin L., Wang C., Zhang,R., Ruan H., Yang J., 2020. Drought stress induced increase of fungi:bacteria ratio in a poplar plantation. Catena, 193, 104607, https://doi.org/10.1016/j.catena.2020.104607.

Thorup-Kristensen K., Magid J., Jensen L.S., 2003. Catch crops and green manures as biological tools in nitrogen management in temperate zones. Agronomy, B.-A, Academic Press, doi: 10.1016/S0065-2113(02)79005-6, pp. 227-302.

Tonitto C., David M.B., Drinkwater L.E., 2006. Replacing bare fallows with cover crops in fertilizer-intensive cropping systems: A meta-analysis of crop yield and N dynamics. Agriculture, Ecosystems & Environment, 112(1): 58-72, https://doi.org/10.1016/j.agee.2005.07.003.

van Groenigen J.W., van Kessel C., Hungate B.A., Oenema O., Powlson D.S., van Groenigen K.J., 2017. Sequestering soil organic carbon: A nitrogen dilemma. Environmental Science & Technology, 51(9): 4738-4739, doi:10.1021/acs.est.7b01427.

Vanzolini J.I., Galantini J.A., Martínez J.M., Suñer L., 2017. Changes in soil pH and phosphorus availability during decomposition of cover crop residues. Archives of Agronomy and Soil Science, 63(13): 1762-1773, https://doi.org/10.1080/03650340.2017.1308493.

Veerman C., Correia T.P., Bastioli B., Biro B., Bouma J., Cienciala E, Emmet B., Frison E., Grand A., Hristov L. et al., 2020. Caring for soil is caring for life (No. KI-02-20-463-EN-N). European Comission, Brussels

Velykis A., Satkus A., Masilionyte L., 2014. Effect of tillage, lime sludge, and cover crop on soil physical state and growth of spring oilseed rape. Zemdirbyste-Agriculture, 101: 347-354.

Villamil M.B., Bollero G.A., Darmody R.G., Simmons F.W., Bullock D.G., 2006. No-till corn/soybean systems including winter cover crops: Effects on soil properties. Soil Science Society of America Journal, 70(6): 1936-1944.

Wang X., Chi Y., Song S., 2024. Important soil microbiota's effects on plants and soils: a comprehensive 30-year systematic literature review. Frontiers in Microbiology, 15:1347745, doi: 10.3389/fmicb.2024.1347745.

Wang Z., Zhao X., Wu P., Chen X., 2015. Effects of water limitation on yield advantage and water use in wheat (Triticum aestivum L.)/maize (Zea mays L.) strip intercropping. European Journal of Agronomy, 71: 149-159.

Wiesmeier M., Lungu M., Hubner R., Cerbari V., 2015. Remediation of degraded arable steepe soils in Moldova using vetch as green manure. Solid Earth, 6: 609-620.

Williams N.D., Petticrew E.L., 2009. Aggregate stability in organically and conventionally farmed soils. Soil Use and Management, 25: 284-292, https://doi.org/10.1111/j.1475-2743.2009.00223.x.

Yang Z., Singh B.R.M., Sitaula B.K., 2004. Fractions of organic carbon in soils under different crop rotations, cover crops and fertilization practices. Nutrient Cycling in Agroecosystems, 70: 161-166, https://doi.org/10.1023/B:FRES.0000048479.30593.ea.

This work was carried out as part of a project funded by the Polish Ministry of Agriculture and Rural Development, implemented by IUNG-PIB under task DC3.0: "Shaping soil retention as part of agricultural drought prevention and rational water management", and the Horizon Europe project No. 101091246 "Nature-Based Solutions for Soil Management"

Author	ORCID
Beata Bartosiewicz	0000-0003-0148-2999
Rafał Wawer	0000-0001-9266-9577
Ludwika Poręba	0000-0002-7987-1102
Grzegorz Siebielec	0000-0001-8089-6123

received 8 May 2025
reviewed 12 June 2025
accepted 10 September 2025

Authors declare no conflict of interest.