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Review

Shaping Soil Properties and Yield of Cereals Using Cover Crops under Conservation Soil Tillage

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Abstract: The aim of this review was to collect current results on the effect of different plants grown as winter and summer cover crops (CC) on the physical, chemical, and biological properties of soil and on the yield of cereal crops grown in a site with CC, using conservation soil tillage. The analyzed studies indicate that CC usually have a positive impact on the physical and biological properties of the soil. Regardless of the plant species used as CC, we can expect an increase in the number of soil microorganisms and an improvement in the activity of soil enzymes. This effect is particularly beneficial in the case of reduced tillage systems. Mixing CC biomass with the topsoil loosens compacted soils and, in the case of light, sandy soils, increasing the capacity of the sorption complex. The size and composition of CC biomass and weather conditions during the vegetation period and during the covering of the soil with plant biomass are of great importance for improving the chemical properties of the soil. A beneficial effect of CC, especially legumes, on the content of the mineral nitrogen in the topsoil is usually observed. Sometimes, an increase in the content of available forms of potassium (K) and/or phosphorus (P) is also achieved. The effect of CC on the content of soil organic carbon (C), total nitrogen (N), or soil pH is less common. CC used in reduced tillage systems can significantly improve the yield and quality of cereal grain, especially when legumes are used as CC in low-fertility soil conditions and at low fertilization levels. However, non-legumes can also play a very positive role in shaping soil properties and improving cereal yield.

Keywords: biological properties; cereal yield; cover crops; chemical properties; physical properties; reduced tillage

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Citation: Wilczewski, E.; Jug, I.; Szpunar-Krok, E.; Staniak, M.; Jug, D. Shaping Soil Properties and Yield of Cereals Using Cover Crops under Conservation Soil Tillage. *Agronomy* **2024**, *14*, 2104. https://doi.org/10.3390/agronomy14092104

Academic Editor: Tie Cai

Received: 2 August 2024
Revised: 11 September 2024
Accepted: 13 September 2024
Published: 15 September 2024

1. Introduction

The growing world population results in an increasing demand for food production [1,2]. On the other hand, the area of agricultural land is gradually decreasing. In just 20 years (between 2000 and 2020), the area of agricultural land decreased by 2% [3]. In this period, the world population increased by 27.8% [4]. As a result, the area of agricultural land per capita decreased by 23.3%. Taking these changes into account, we should expect increasing difficulties in meeting the nutritional needs of the growing population. One of the solutions of this problem is increasing crop yield per unit area to meet human food needs. Moreover, it is widely known that meeting human nutritional needs will be possible after changing the way we eat by increasing the consumption of plant products instead of animal products [5,6]. As a result, a decrease in the number of farm animals and the amount of farmyard manure production may be expected. Taking into account the influence of farmyard manure fertilization on the physical, chemical, and biological properties of soil [7,8], especially a decrease in bulk density, penetration resistance, and an increase in hydraulic conductivity, soil aggregation and aggregate-associated carbon, an increase of soil organic carbon as well as an increase in the number of soil microorganisms, we could predict deterioration of the soil properties as a result of reducing of farmyard manure production and usage [9–11]. To prevent unfavorable changes, it is increasingly necessary to supply the soil with another type of organic matter, substituting farmyard manure. To maintain a high level of soil productivity and sustainable agrotechnology on the other hand, it is necessary to look for alternative methods to improve soil biological activity. Green manuring may be an essential agrotechnology practice in conditions without farmyard manure. Winter and summer CC used as green manure may be an effective source of organic matter and may have a very positive effect on the physical properties of soil and its biological activity [12–14]. CC biomass is not as effective as farmyard manure in terms of its impact on soil properties, but a systematic supply of plant biomass from green manures to the soil (every year or every other year) contributes to increasing the resources of soil organic matter (SOM), which has a significant impact on plant production [15,16]. It is an important source of N and other nutrients necessary for plant growth [17]. It also plays an important role in retaining nutrients and water in the soil, which is particularly important in highly weathered soils with a low cation exchange capacity [18]. That reason is why it is so important to cultivate summer CC, which, in addition to providing organic matter to the soil, may reduce the losses of nutrients unused by the main crop. Soil covered with both mulch from summer CC, as well as by live plants from winter CC, is protected against erosion during the winter, and during the sowing period of spring crops, it usually has more favorable moisture and content of available forms of fertilizer components [19–21]. If organic matter is not supplied to the soil, the soil is gradually impoverished. According to estimates by Sanderman et al. [22], agricultural land use has resulted in the loss of 133 Pg of C from the top 2 m of soil over the last 200 years. Alternative production systems and conventional systems can play a fundamental role in soil carbon sequestration, such as conservation tillage, which is characterized by reduced tillage (including no-tillage systems), more diverse crop succession, and permanent vegetation cover, including increased cover cropping frequency. Any simplifications in soil cultivation, limiting interference with the topsoil, and the use of organic fertilizers, contribute to improving soil properties and increasing biological activity, which helps maintain its productivity and fertility [23]. In temperate climate conditions, in soils covered by a reduced tillage system, Szostek et al. [23] obtained higher contents of soil organic carbon (SOC), total N, and SOM fractions than in the conventional tillage system and organic farming.

Different plants used as CC are characterized by a different efficiency and ability to take up and accumulate nutrients. In addition, the rate of mineralization of their biomass is different [24–26]. Many studies have shown the special value of legume crops [21,27,28]. They increase the activity of soil microorganisms, improve the physical and chemical properties of the soil, and suppress weeds [28]. They can also interrupt the development cycles of diseases, insects, and other pests [29]. Legume crop biomass undergo fast mineralization in the soil, which can support the growth of plants grown after them from the very early stages of their development [21]. The beneficial effect of these plants on the soil is particularly important on the conditions of their long-term use as CC [30]. Biomass mineralization of non-legume crops is usually slower, and their subsequent impact mainly concerns traits formed in the later stages of development of plants grown after them [31–33]. Taking this effect into account, the aim of this review was to collect current results on the effect of different plants grown as winter and summer CC on the physical, chemical, and biological properties of soil and on the yield of cereal crops grown in a site with CC, using conservation soil tillage.

2. Cover Crop Biomass

CC, besides its positive impact on the biological, physical, and chemical properties of soil, are an important source of nutrients for plants grown after them [17,18]. Therefore, it is very important to produce significant biomass, which can play an important role as green manure. Therefore, the right choice of plant species used for this purpose is very important. Other factors (sowing parameters, fertilization, and weather conditions) also play an important role. In conservation tillage, the planting of CC is usually carried out into undisturbed soil by opening a narrow trench [30]. For this purpose, seed drills equipped with disk coulters are used (Figure 1).

Figure 1. Sowing of CC seeds in conservation tillage conditions. (Photo: E. Wilczewski).

To obtain a positive effect of CC, it is necessary for plants to produce significant biomass that can substantially affect the growth conditions of the main crop. The amount of biomass produced by CC depends on many factors. The most important are total rainfall, soil fertility, the type of plant grown, mineral fertilization, sowing time, the length of the growing season, frosts, and in the case of winter CC, also the conditions of plant wintering. The total dry matter yield of CC ranges from 1.6 Mg ha^{-1}, in unfavorable conditions [34], to even 24.1 Mg ha^{-1}, in very good soil and water conditions [35]. In average conditions, 2.5–6.5 Mg ha^{-1} dry matter of summer CC may usually be obtained [21,24–26,36]. The disadvantage of summer CC is the high dependence of the biomass yield on weather conditions, especially precipitation during the sowing period and during the vegetative growth of plants [37–39]. This results in high variability over the years, both in terms of the biomass produced and the nutrients accumulated in it [39–42]. Non-legume plants (Figures 2 and 3), especially white mustard, oilseed radish, lacy phacelia, and ryegrass, are characterized by high yield fidelity when grown both as single-species crops and as mixtures [26,34,43–45]. Tribouillois et al. [38], based on studies including 36 species of plants used as CC, stated that some Fabaceae species are sensitive to high temperatures, whereas species from Poaceae and Brassicaceae families were more resistant to water deficit and germinate under a low base water potential.

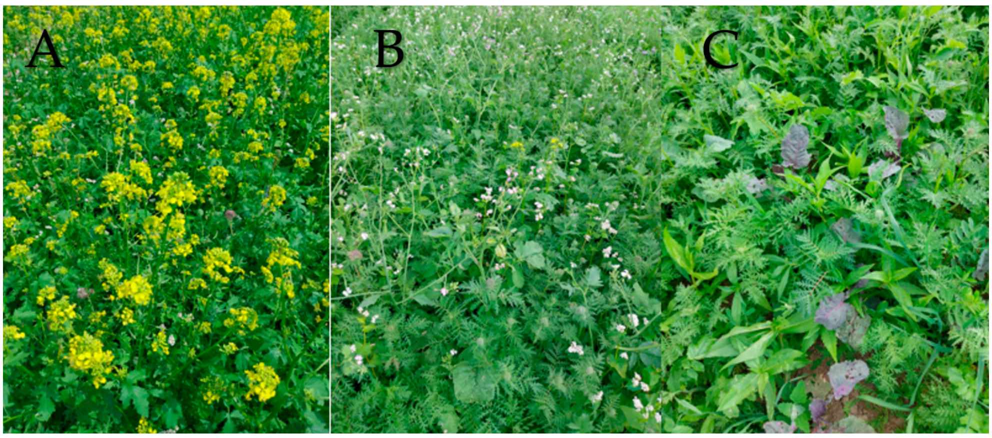

Figure 2. White mustard (**A**), oilseed radish (**B**), and tansy phacelia (**A**–**C**) as components of non-legume mixtures of plants grown as summer CC (Photo: M. Staniak).

Figure 3. Different varieties of oilseed radish as winter (**A**) or summer (**B**) CC (Photo: D. Jug and E. Wilczewski).

According to Wendling et al. [45], mixtures with high species diversity ensure a stable and high biomass production with a low risk of failure. The dry biomass yield of winter CC usually ranges from 3.5 to 9.5 Mg ha^{-1} [46–51]. Particularly useful as winter CC are hairy vetch, winter rye, ryegrass, crimson clover, winter oilseed rape, and mixtures of these crops. In regions with mild winters, black oat, blue lupin, oilseed radish, and turnip are also useful [46,49]. The share of post-harvest residues in the total biomass yield of winter CC is usually from 11 to 26% [46]. In the total biomass, winter CC can accumulate from 33 to 185 kg N ha^{-1}, depending on the plant species and harvest date [40,47,52,53].

In conservation tillage, the biomass of CC is usually retained on the soil surface [28]. In the second half of autumn or in winter, the plant biomass is usually damaged by frost and covers the soil surface (Figure 4). In the spring, the biomass can be mixed with the soil, or the following crop may be sown directly into the mulch of CC. Plants with stiff stems, such as white mustard, may remain upright until spring (Figure 5). In this case, it is necessary to mow or mechanically break the stems before sowing the main crop.

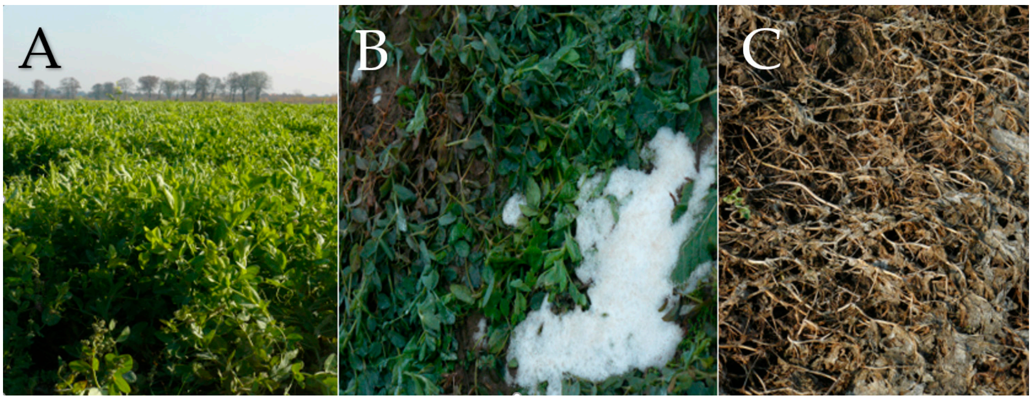

Figure 4. Field pea as CC in autumn (**A**), winter (**B**), and early spring (**C**) (Photo: E. Wilczewski).

Biomass from CC is used as green manure for various plants (cereals, root crops, potatoes, and vegetables) grown in the following year. Using the entire biomass produced by CC as green manure usually produces better results than using only post-harvest residues for this purpose. The share of it in the entire biomass is usually 20–40%, depending on the plant species and soil and weather conditions [21,24–26]. In a study by Redin et al. [46] conducted in very good soil and weather conditions with the total biomass yield ranging from 6.4 to 24.1 Mg ha^{-1}, this share ranged from 6.3% for Jack bean to 10.5% for Dwarf pigeonpea and Gray mucuna. The highest share of post-harvest residues (72%) was found for Italian ryegrass [34] and a mixture of phacelia with radish and turnip (46.1%) [24]. The uptake of nitrogen by CC and thus the reduction in its leaching from the upper soil layer depended on the plant species, weather conditions, and agrotechnics used [40,41]. A high N uptake potential (90–120 kg ha^{-1}) had legumes [42], white mustard, and fodder radish [31,54,55]. Smaller amounts of N (60–80 kg ha^{-1}) were taken up by rye and oats [40,52] and turnip rape [25,42].

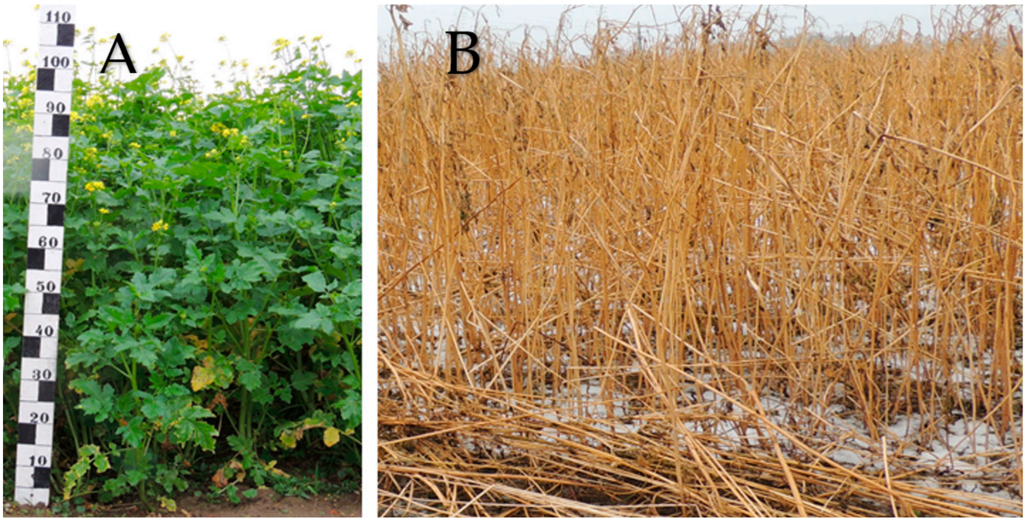

Figure 5. White mustard as CC in autumn (**A**) and late winter (**B**) (Photo: E. Wilczewski).

3. The Influence of Cover Crops on Soil Properties and Reducing the Loss of Nutrients Depending on Tillage System

3.1. Biological Properties

Soil microorganisms play an important role in the processes of decomposition of organic residues and enrichment of the soil with nutrients, biological activity, growth, antibiotic substances, participation in the formation of soil structure, detoxification of agrochemicals, and organic pollutants [56,57]. In this way, they contribute to maintaining the balance in the soil environment. According to Marinari et al. [58], more than 80% of all soil processes are closely linked to the activity of microorganisms.

Soil fertility, and thus its biological activity, can be increased using various agrotechnical treatments, including appropriate crop rotation with catch crops, organic fertilization, regulating water relations in the soil, and appropriate soil cultivation [59,60]. The method of cultivation affects the quantity and quality of organic matter, soil structure and moisture, pH, oxygen content, as well as the number and diversity of soil organisms. Intensive cultivation leads to the degradation of the soil environment, therefore limiting the plowing system and using tillage simplifications to help preserve the natural environment and support natural biological processes in the soil [61]. No-tillage systems improve soil properties, mainly by increasing and maintaining higher levels of organic C, which is crucial for increasing production stability. Significantly higher levels of organic C and total N in simplified systems were observed especially after a long period of soil use in this system: after 10 years [62], after 22 years [63], and even after more than 30 years [64,65], which indicates a high durability and stability of such an agricultural ecosystem.

The method of tillage significantly affects the populations of soil microorganisms. Both the biomass and the diversity of soil microorganisms are much higher in the conservation system compared to plow tillage. This is confirmed by Gajda's research [60], which showed that in the soil under winter wheat cultivated in a reduced tillage system, the number of soil microorganisms was higher by an average of 20% compared to the conventional system, both at a depth of 0–15 cm and 15–30 cm. In reduced tillage, higher dehydrogenase activity and ammonification and nitrification strength of soils were shown, which is also confirmed by other authors [66,67]. Growing rough oats in a no-tillage system has also shown many benefits related to soil microbiology and nutrient cycling [66]. It promoted greater diversity and activity of microorganisms in the soil thanks to the preservation of the natural soil structure, and it also contributed to an increase in the amount of organic C in the soil. Microorganisms, such as bacteria and fungi, processing crop residues, create stable organic material that have a beneficial effect on the soil structure, its ability to retain water, and the availability of nutrients for plants. This in turn contributes to improved soil health, better nutrient cycling, and a more balanced approach to the cultivation system. The method of cultivation also has a significant impact on the enzymatic activity of the soil, which is manifested by greater activity of soil enzymes in simplified systems compared to conventional ones. In a study by Harasim et al. [68], conservation tillage increased the activity of dehydrogenases and urease (on average, by 21.3% and 24.0%, respectively), regardless of the depth, compared to traditional plow tillage. Similarly, in a study by Lupwayi et al. [69], the conservation system showed higher (on average by 50%) activity of β-glucosidase, an enzyme involved in the carbon cycle, compared to the conventional system. The tillage system also affects the populations of earthworms and other mesofauna. Reducing the intensity of tillage reduces soil disturbance. The lack of soil turning protects its natural structure and helps save moisture. In turn, the increased amount of crop residues and organic biomass that characterize these systems provides more food and improves the living conditions of soil organisms [70]. In studies by Lenart and Sławiński [65], under the conditions of long-term (33 years) direct sowing, the number and mass of earthworms were 2–3 times higher, both in spring and autumn, compared to plow cultivation. Also, studies by Pelosi et al. [71] showed that the total biomass of earthworms in the no-tillage system with the participation of CC (alfalfa) was 4.2 times higher than in the conventional system. A greater functional diversity of earthworms was also observed at a lower cultivation intensity [72]. Earthworms help mitigate the effects of soil compaction that accompanies no-till systems. By digging tunnels in the soil, they create macroaggregates that loosen the soil, increase its water stability and permeability, and improve ventilation and air access. This allows plant roots to develop freely, which is especially important in the case of compact soils [73,74]. The method of tillage also affects the number and activity of other soil mesofauna organisms. The Collembola and Acari families are widely represented in the soil. They have a beneficial effect on soil fertility and respond relatively quickly to any changes caused by agricultural practices [75]. For this reason, they are considered a good indicator of the quality of the soil environment [76]. Studies show that greater numbers and diversity of Collembola and Acari are found in soil cultivated using the no-tillage system (direct sowing) compared to the reduced system and traditional tillage [77].

In reduced tillage systems CC play a special role, as they have a beneficial effect on the biological properties of the soil and also fulfill many different ecological functions. Keeping CC on the soil surface reduces the soil temperature range, retains moisture, and stabilizes the gradient of organic matter transformations [78]. In addition, they protect the soil in the winter from erosion caused by the direct impact of rainfall and sun. The biomass of CC plants is also an important source of organic C for soil microorganisms, which help temporarily immobilize and reduce losses of nutrients, thus engaging in C and nutrient cycling [63]. However, it depends largely on the CC species. Productive CC with low lignin content (e.g., clover, common vetch, field pea, white mustard, and blue phacelia) decompose relatively quickly and stimulate organic matter turnover and activate soil microorganisms. Thanks to this, the processes of C and nutrient circulation are balanced, which is the basis of soil fertility. In the case of plants containing a lot of lignin (e.g., winter rye, triticale, sheep, and alfalfa), the decomposition process is hindered by calcium compounds and at the same time stimulated by high N concentration. Organic N can undergo mineralization or be immobilized, which changes the availability of mineral N for subsequent plants and the functioning of the entire ecosystem [79].

Long-term no-tillage farming practices combined with the use of CC have a particularly positive effect on soil microbiome activity. Barel et al. [80] showed that monocultures of perennial ryegrass, white clover, common vetch, common radish, and their mixtures had a beneficial effect on the microbiological properties of the soil, in particular on the biomass of bacteria and fungi, their quantitative ratio, and the concentration of ergosterol. However, some of these properties differed depending on the CC species and the previous main crop. Other authors have shown beneficial effects of hairy vetch [81], common vetch [64], yellow lupine, and pea [82] on the population size and diversity of soil microorganisms. Cultivation of these CC under no-tillage conditions significantly increased microbial biomass (especially Gram-positive bacteria), N mineralization, and promoted the sequestration of more C and N in stable SOM fractions, which had a beneficial effect on the yield of the main crop. In turn, Nevins et al. [67] showed that the rye CC promoted the development of soil bacteria such as Acidobacteria, Proteobacteria, and Actinobacteria, while the white mustard catch crop increased the share of bacteria associated with the plant rhizosphere, such as *Rhizobiales* and *Bacillales*.

The beneficial effect of CC on soil microbiological activity was also demonstrated by Chavarria et al. [83]. The inclusion of mixtures consisting of oats, common vetch, and common radish in the crop rotation contributed to an increase in the activity of soil enzymes, especially dehydrogenase activity and fluorescein diacetate hydrolysis by 38.1% and 35.3%, respectively, compared to the control treatment, and no negative effect of CC on the yield of the main crop was demonstrated. Also, Kwiatkowski et al. [84] showed an increase in soil enzymatic activity (dehydrogenase by 10.4%, urease by 16.3%) in no-tillage system conditions using various CC: white mustard, blue phacelia, and a mixture of field bean and field vetch. Dehydrogenase is one of the indicators of biological soil functionality, which reflects redox processes and a respiration of soil microorganisms, while urease is an enzyme responsible for converting urea into ammonia. Other authors also report an increase in soil enzymatic activity under the influence of CC [12,64,67,82,85–87].

CC may increase the availability of phosphorus (P) for main crops, improving their nutrition with this element and consequently having a positive effect on yields. The key process is the decomposition of CC biomass, but P availability also increases due to an increase in the biomass of soil microorganisms and the abundance of mycorrhiza or phosphatase activity, which affects the P cycle in the soil [13,88]. CC have been shown to be the most effective in systems with low P availability, but the species of plant used as CC, the level of fertilization, and the cultivation system are also important [88].

CC protects the soil against erosion and moisture loss, improves its fertility and structure, and inhibits the growth of weeds through physical and chemical intervention, which is confirmed by numerous authors. In a study by St Aime et al. [49], the use of a mixture of five CCs (peas, rye, incarnate clover, hairy vetch, and oats) grown in the autumn–winter season effectively reduced a weed infestation of the main crop (weed reduction by over 90%) and did not deteriorate water conditions of the habitat. In addition, the biological activity of the soil increased (by 43%) compared to chemical fallow, which contributed to the improvement of soil health indicators, such as soil respirometry, and consequently had a positive effect on the yield of the main crop (soybean). In other studies [89], CC (incarnate clover and rye) reduced the number and biomass of weeds but did not allow for the complete elimination of pre-emergence herbicides in soybean cultivation. However, they had a positive effect on the content of organic matter, the number of bacterial and fungal populations, and the activity of esterase.

A key factor influencing soil microbiology is the water condition. Soil microorganisms need water to carry out their life processes. Optimal moisture levels enable enzyme activity and microbial metabolism. Excessive moisture or soil compaction restricts water flow, which can lead to soil hypoxia, inhibiting microbial activity. In turn, water deficiency restricts the vital functions and activity of soil microorganisms. Some may even enter a dormant state or spore form in response to drought. This is confirmed by the results of Calderon et al. [90], who showed that CC cultivation (mixture of oat, pea, flax, rapeseed, lentil, vetch, white clover, barley, safflower, and phacelia) had a short-term effect on soil microbial activity in semi-arid wheat-based rotations, while irrigation significantly increased soil enzymatic activity. In a semi-arid environment, a longer period was needed to observe the beneficial effects of CC on the microbial community structure, enzymatic activity, and C sequestration in the soil. Water is one of the main factors shaping the structure and activity of microorganisms. It promotes the decomposition of organic biomass, root proliferation, and microbial development. Giving up plow cultivation reduces water losses from the soil by limiting evaporation and increasing water retention, which has a beneficial effect on soil microorganisms [91].

3.2. Physical Properties

Improving soil physical properties is one important step in soil conservation. Cover cropping (different types of crops and time for cropping) can improve soil physical properties, which can lead to the reduction of soil loss and thereby improve soil productivity and environmental quality [92].

CC can modify soil structure indirectly through their effects on SOM content, aggregate stability, and microbial activity. Well-aggregated soil has large, stable pores that promote water infiltration, aeration, and root penetration, while poor soil structure, often caused by compaction or erosion, restricts root growth [93] and water movement, leading to decreased productivity [94,95]. Haruna and Nkongolo [96] observed a 3.5% decrease in soil bulk density as an effect of rye use as CC. It may have profound effects on soil structure through their root growth, exudation of organic compounds, and residue decomposition. Roots of CC play a crucial role in soil structure formation by exerting physical forces that aggregate soil particles and create pore spaces [97]. According to Abdollahi et al. [98], the use of fodder radish as CC increased air-filled porosity at −10 kPa, air permeability, and pore organization reduced the value of blocked air porosity both on reduced and conventional tillage treatments. CC created continuous macropores and in this way improved the conditions for water and gas transport and root growth. CC thus alleviated the effect of tillage pan (e.g., plough pan) compaction in all tillage treatments. Extensive root systems of CC (forage radish, rapeseed, and rye), particularly deep-rooted species, penetrate deep into the soil profile, loosening compacted layers and improving soil aeration and drainage [99–101]. Root exudates, such as polysaccharides and mucilages, act as binding agents, promoting soil aggregation and stability [102]. Additionally, CC roots facilitate the development of macro- and micro-aggregates by providing habitats for soil organisms that contribute to organic matter decomposition and aggregation.

Upon termination, CC contribute organic residues to the soil, which undergo decomposition and incorporation into the soil matrix. The decomposition of CC residues releases carbon compounds and nutrients, stimulating microbial activity [103] and enhancing soil aggregation. Residues from leguminous CC, rich in nitrogen, enhance microbial biomass and promote the formation of stable soil aggregates. The incorporation of CC residues also improves soil water retention by increasing SOM content and enhancing soil structure [104].

Different forms of soil water (gravitational, capillary, hygroscopic, and chemically bound) have different roles, impacts, and importance in complex crop production systems [105]. Soil water dynamics are influenced by factors such as texture, structure, and organic matter content, impacting plant water uptake and drought resilience [106,107]. CC enhance soil aggregate stability, which influences water infiltration and retention. Haruna et al. [92] states that CC can reduce surface seal formation, which increases water infiltration and reduced runoff. Well-aggregated soil has a higher macroporosity, facilitating rapid water infiltration and reducing surface runoff [108–110]. CC contributes to SOM accumulation, which enhances soil water retention capacity and prevents excessive drainage. The incorporation of CC residues increases soil water-holding capacity, particularly in sandy soils with low inherent organic matter content [105]. Furthermore, CC roots facilitate the formation of macropores, allowing water to infiltrate deeper into the soil profile and reducing the risk of waterlogging.

SOM plays a crucial role in soil physics by improving soil structure, water retention, [111,112] and nutrient cycling. It enhances aggregation, increases porosity, and enhances soil's cation exchange capacity, aiding in nutrient retention and availability [105]. CC play a crucial role in enhancing SOM content, thereby contributing to soil fertility, structure, and overall health [113]. The incorporation of CC (perennial ryegrass, rapeseed, and rye) into agricultural systems promotes the accumulation of organic residues, which decompose and enrich the soil with C and nutrients [114]. CC influence SOM through various mechanisms, including the following: (I) aboveground biomass production: producing aboveground biomass, including leaves, stems, and roots, which contribute to SOM when incorporated into the soil; (II) belowground root exudation: the extensive root systems of CC release organic compounds, known as root exudates, into the soil.

SOM plays a crucial role in preventing soil compaction and maintaining soil structure [111], and it contributes to compaction prevention through various mechanisms, including the following: (a) Improved soil structure: SOM promotes the formation and stabilization of soil aggregates, which enhance soil structure and resistance to compaction [115] (the binding agents present in SOM, such as humic substances and polysaccharides, facilitate the aggregation of soil particles, creating stable soil aggregates that resist compression). (b) Increased soil porosity: SOM creates macropores and micropores within the soil matrix [116]. These pores provide pathways for water infiltration, root penetration, and gas exchange, reducing the likelihood of soil compaction. Additionally, SOM improves soil water retention capacity, increases soil moisture content, and alleviates the effects of compaction [111]; CC associated with conservation soil tillage plays a crucial role in soil aggregation, organic matter decomposition, and nutrient cycling, thereby contributing to soil structure and compaction prevention [89].

CC exert profound effects on the physical properties of soil, influencing soil structure, texture, water dynamics, and compaction. Through their root growth, residue decomposition, and organic matter incorporation, CC enhance soil aggregation, water retention, and aeration, thereby improving soil health and productivity. Understanding the interactions between CC and soil physical properties is essential for implementing sustainable agricultural practices that promote soil conservation, crop resilience, and ecosystem stability [117]. According to Abdollahi and Munkholm [118], five years of using fodder radish as a CC-alleviated plow pan compaction led to a 20–40 cm depth by reducing penetration resistance. A significant interaction between tillage and cover crop treatments indicated the potential benefit of using a combination of cover crops and direct drilling to produce better soil friability.

Studies reporting on CC combined with reduced or conservation tillage are rare. Many studies have focused on investigating partial elements of reduced or conservation tillage or CC, but studies of their combinations are rare [118]. Changes in soil physics as a result of a combination of different approaches to conservation soil tillage and CC [114] are not universal or uniformly accepted, and conducted studies provided different results [119]. Many factors directly or indirectly influence the results of the strongest factors: soil type, meteorological elements (precipitation, temperature, wind, etc.), and soil and crop management. For some parameters of soil physics, when considered the most important (soil compaction, bulk density, soil structure, and porosity), the authors report both positive and negative reactions to combinations of conservation tillage and CC. Soil compaction, bulk density, soil structure, and porosity can be alleviated using CC (mostly forage radish, rapeseed, and rye) [118–122], which implies the possibility for the application of reduced or conservation tillage [100] instead of intensive conventional tillage.

3.3. Chemical Properties

Many studies have shown that the presence of CC affects the chemical composition of the soil. CC can increase the level of SOC or reduce the rate of its depletion as a result of additional C input from aboveground and belowground biomass [109,123]. The accumulation of SOC in the topsoil depends on many factors, including the amount of biomass and CC species, soil type, cultivation system, initial soil C level, and climatic conditions [124–128]. In maize cultivation, the combination of no-tillage and CC systems has a stronger effect on SOC accumulation in the topsoil than the separate use of these practices [129]. The inclusion of CC in no-tillage systems leads to a higher SOC accumulation from 0.1 to 1.0 Mg ha^{-1} yr^{-1} compared to no-tillage and no CC systems [124]. Poeplau and Don [125] estimated that CC can sequester about 0.32 $\pm$ 0.08 Mg ha^{-1} yr^{-1} carbon to a depth of 22 cm of soil. In the first few years after CC introduction in different cropping systems, no increase in SOC is usually observed, but the effects of their presence are noticeable in the long term [130]. The lack of accumulation of SOC and soil total N during the year may be due to the rapid degradation of plant residues after their introduction into the soil. [123]. In the experiment conducted in temperate climate conditions (Poland) on two types of soil (Luvisol and Phaeozem), CC biomass (field pea) introduced in subsequent years, compared to the control without CC, had no effect on the soil pH, SOC, or total N content [131]. Also, the incorporation time of CC (in the autumn or mulched and incorporated in the spring vs. a control—without CC) did not significantly affect the chemical properties of typical Alfisol formed of a sandy loam. Other studies have reported contradictory results on this issue. In the CC/rice/CC/rice crop rotation in a no-tillage system, an increase in SOC content at a depth of 0–5 cm was observed from the first year of CC presence. The presence of CC contributed more to soil fertility than fallow [132]. Based on a 2-year study conducted in Missouri, USA, it was shown that the presence of CC in a corn–soybean rotation in a no-tillage system had a positive effect on the SOC content in the topsoil [133]. In a long-term experiment conducted in Switzerland, the presence of well-developed CC, even for only two months of the year, increased the content of SOC and total N in the soil, especially in the case of reduced tillage, and allowed maintaining the wheat yield at the level observed in the plow and minimum tillage treatments [134]. In a 16-year experiment (northern France), the SOC amount remained stable over time in conventional and low-input systems (+3% and +1%, respectively), increased slightly in the organic system (+12%) and increased significantly in the topsoil (0–10 cm) in the conservation agriculture system (+24%). The SOC increase observed in the conservation agriculture system was attributed to one or more of the following practices: zero tillage, permanent soil cover, and crop diversification [135]. Most of the changes in soil chemical properties under the influence of CC are limited to the upper soil layer. Olson and Al-Kaisi [136], after 20 years in the no-tillage system, observed a greater accumulation of SOC in the soil to a depth of 20 cm, but the accumulation of SOC in the 20–35 cm layer was lower than under the influence of moldboard plow cultivation. The accumulation of SOC in deeper no-tillage soil depths may be facilitated by the use of deep-rooting CC [127].

It has been shown in many studies [30,132,134,137,138], that the presence of CC in crop rotations, including legumes, is important not only because of their effect on increasing the level of SOC in the soil or reducing the rate of its depletion but also retaining plant-available N in organic matter. In the case of legumes, the increase in soil fertility is associated not only with the supply of biomass, but also with N from symbiotic fixation of atmospheric N (BNF) [139,140]. Legumes in crop rotations also contribute to solubilizing unsolvable P in the soil [26].

As a result of the decomposition of organic matter, many organic compounds are released into the soil [141]. The use of CC in no-tillage systems can significantly improve soil fertility [132]. In addition to the large amount of roots present in the soil (from 20 to 50% of biomass), plants release root exudates into the soil, containing more than 200 compounds of Ca (organic acids, phenolic acids, amino acids, etc.), which have a major impact on the soil microbial community and biological processes. Root lysis and root exudates contribute significant quantities of carbon deposited in sub-surface soil. Amounts from 5 to 21% of photosynthetically bound C is released into the rhizosphere as root exudates [142]. In addition, soil microorganisms associated with CC root systems have the potential to release nutrients and transform them into forms more available to plants [134], e.g., arbuscular mycorrhizal fungi and rhizobia in the rhizosphere of legumes can increase the availability of N and P for subsequent crops [143,144].

In conventional cereal production systems, nitrate losses due to leaching range from 10% to 30% of applied N [145]. In the long term, CC cultivation is an effective way to reduce N leaching from soil (from 36 to 62%) and maintain long-term nitrate concentrations below 50 mg L^{-1}, and this positive effect decreases with decreasing CC frequency [34]. Based on research conducted in the mid-Atlantic, USA, Hirsh et al. [146] recommend incorporating CC into minimum tillage systems to capture residual N. This allows for a reduction in inorganic N content in the soil. Deep-rooting CC sown in autumn can potentially take up residual N and recycle some of it for following crops. The use of CC promotes a reduction in nitrate content in the upper 60–120 cm soil depths in autumn. Since in temperate climate conditions, an increase in the share of legumes in crop rotations reduces C input to the soil and leads to greater N leaching, the use of CC in cereal–legume rotations is recommended to increase N_2 fixation and reduce nitrate leaching [147]. Based on the analysis of many studies covering different countries, climate zones, and management practices, Abdalla et al. [148] emphasized that CC cultivation significantly reduces N leaching and increases SOC sequestration without significantly affecting direct N_2O emissions. It can also indirectly increase N_2O emissions (NO_3 leaching) due to the introduction of organic substrates, the release of N during decomposition, or the increase in soil water content in the summer [149]. In a study conducted in sandy loam soils in Georgia, USA, a non-legume cover crop (rye) was shown to be superior to a legume (hairy vetch and crimson clover) in its influence to increase SOC and N content [150]. Under these conditions, CC and N fertilization can increase C input and storage in arable and untilled soils, and growing a mixture of hairy vetch and rye results in greater SOC accumulation than monocultures [151]. CC and fertilization with 80–180 kg N ha^{-1} yr^{-1} can increase soil organic C and N concentrations by up to 4–12% compared with no CC or N fertilization. The combination of conservation tillage, a mix of legume and non-legume crops, and reduced N fertilization rates may show greater potential to maintain yields and improve soil and water quality compared with the use of any of these practices alone [140]. In the Canadian prairies, the inclusion of legumes (field pea, lentil, and faba bean) in no-tillage soils increased soil fertility and improved soil N cycling in canola and spring wheat cropping systems. A total of 40–65% in crop N uptake came from in-crop N mineralization, particularly by legumes, compared to 35–60% from N fertilizers, and the magnitude and timing of these benefits depended largely on the legume species, crop purpose (greater in green manure than seed crops), and specific site conditions [152]. In temperate climate conditions (Poland), the cultivation of field pea as a CC increased the mineral N content in the arable layer of Luvisol soil, which was observed in the early spring before sowing and during the barley tillering period (successive plant). It was particularly high in the soil where CC was left for winter as mulch, which can be associated with delayed mineralization of pea biomass [21].

As a result of the decomposition of organic residues, many organic compounds are released into the soil and/or synthesized by the microflora that decompose them [141]. The rate of nutrient release depends on the biochemical and chemical composition of the residue, as well as the microbial activity in the soil [33,153]. N release from crop residues varies with residue quality [154], and the best single predictors for net N mineralization are the C/N ratio and the N content of CC residues [155], while lignin concentration is a good predictor of soil C mineralization. Net N mineralization is significantly and negatively related to both shoot and root C/N ratios. At a soil temperature of 10 °C, the C/N ratio affects N mineralization from CC residues mainly in the first 2 weeks, while net C mineralization is significantly limited by lignin content [156]. Biomass decomposition is faster in crop residues with low C/N ratios, such as legumes [157], where the ratio is <20 [158], which in turn results in a rapid increase in microbial activity leading to increased SOC decomposition [159]. Based on many years of experiments in various regions of France, it has been shown that in soils with a high C/N ratio (>11), N availability may limit

SOC decomposition and the rate of N net mineralization from SOM may decrease due to greater N immobilization by microorganisms [160]. In another study [123] conducted in the temperate, humid region of Washington state, silt loam soil showed increased organic C content in soil with CC that produced residues with C:N ratios >30. The effect of CC on SOC building was related to the size of the C input. Due to the higher CC biomass yield (>4 Mg ha^{-1}), cereal rye and annual ryegrass were better suited for building SOC compared to Austrian winter pea, hairy vetch, and canola.

The rate of decomposition of plant residues introduced into the soil also depends on the CC species. Legumes decompose faster, enabling faster delivery of nutrients to the soil, while non-legumes tend to accumulate and decompose slower. Hence, the combined supply of legume and non-legume residues promotes the differential release of nutrients such as N, K, P, Ca, and Mg into the soil [33]. Also in studies conducted in the no-tillage system in the Brazilian Cerrado on acidic clayey loam soil, CC did not cause changes in soil chemical properties compared to the fallow, but in the CC/cash crops/CC/cash crops rotation, a decrease in soil pH, Al, and H+Al was observed, as well as an increase in Ca, Mg, K, and Fe contents [161]. In temperate climate conditions (Poland), in a reduced tillage system, the use of field pea as CC significantly increased the available K content in Luvisol and Phaeozem soils [131]. Studies by Damon et al. [162] indicate a beneficial effect of CC on P content in the soil. The effect of CC on P uptake by the main crop depends on many factors, and its transfer may occur via CC residues, organic anion exudates, root-exuded enzymes, and microbial interactions. As organic residues decompose, P is released into the soil, which increases its availability to subsequent plants [141]. The effect of CC on soil P content also depends on the soil type. The use of field pea as CC in the reduced tillage system increased the concentration of available P in the Phaeozem soil, but no such effect was found in the Luvisol soil [131]. Villamil et al. [121], using winter CC in a no-tillage corn–soybean rotation for at least 5 years on silt loam soils, observed a decrease in soil P content due to its absorption and transformation of available P into organic forms. From an environmental protection point of view, this is beneficial because it reduces the potential loss of P due to leaching. Long-term use of CC (ruzigrass) caused a decrease in P availability in a no-tillage production system of corn [163] and soybeans [164]. CC cultivation for 4 years, in both conventional and no-tillage cultivation systems, increased SOC content, but nutrient recycling by CC was not sufficient to maintain P, K^{+}, Fe^{3+}, and Mn^{2+} contents in the soil [165].

The literature emphasizes the role of CC in limiting the migration of nutrients into deeper soil layers, in particular N [166], P [131,166], and K [131]. However, there are ambiguous opinions regarding the effect of CC in reduced tillage systems on the chemical composition of the soil at its different levels. Sharma et al. [167] indicate that the use of CC can change the chemical properties of the soil, especially in its top layer. In an experiment conducted in Nebraska, in large-scale production fields, CC was used into a no-tillage seed maize or soybean cropping system. They found a positive effect of CC on the content of exchangeable K, Mg, Na, cation exchange capacity, and soil micronutrients (Zn, B, Fe, and Mn). In the soil, CC increased the exchangeable K concentration below the 5 cm soil layer, the cation exchange capacity, and the exchangeable Mg concentration in the 20–40 cm soil layer. CC also reduced the Na concentration at a 20 to 40 cm soil depth but had no effect on the exchangeable Ca concentrations. CC showed the potential to maintain optimal levels of Zn, B, Fe, and Mn in the 0–5 cm layer. In other studies conducted on Red Latosol in Brazil, in no-tillage and conventional cultivation systems, CC (sun hemp and millet) did not change the chemical properties of the soil at depths of 0–10 cm and 10–20 cm [168].

The effect of CC on soil pH is ambiguous. It can affect soil pH as a result of acidic secretions from plant roots [168], causing a decrease in soil pH [132,168,169]. As a result of many years of conservation practices with no-till, CC, and limited inputs, soils contained more SOC and were more acidic than soils under conventional practices with tillage and bare soil between the two cash crops. The positive effects of conservation practices may be limited by carbon saturation. If the soil reaches its carbon potential, it will not be able to sequester more organic C [163]. In turn, Rankoth et al. [133], growing cereal mixture as CC in a no-till system, observed an increase in the amount of SOC and an increase in soil pH. A temporary increase in soil pH often occurs during the decomposition of residues, and the causes include the following: oxidation of organic acid anions present in decomposing residues, ammonification of residue N, specific adsorption of organic molecules formed during decomposition, and reduction reactions induced by anaerobes [141].

3.4. Reducing the Loss of Nutrients from the Soil

Nutrient loss from soil is a critical challenge facing modern agriculture, with significant implications for agricultural productivity, environmental sustainability, and food security. As it is known, the magnitude of nutrient loss from the soil (such as leaching, volatilization, and reutilization) is under the influence of many factors, external and internal, and anthropogenic and/or natural-driven causes. Excessive nutrient runoff and leaching increase the cost of production for farmers and contribute to water quality deterioration [170], which can lead to soil degradation and reduced crop yields [171]. Therefore, implementing effective strategies to reduce soil nutrient loss is essential to maintain soil fertility [172], protect water quality, and promote sustainable agriculture. There are several strategies (techniques and practices) aimed at reducing soil nutrient loss: catch crops [173], cover crops, crop rotation, mulching, conservation tillage, nutrient management planning, contour farming, buffer strips, the use of nutrient rich amendments, and other soil conservation practices.

Crop rotation is a widely recognized strategy for reducing nutrient loss from soil while promoting soil fertility and crop productivity. By rotating different crops in a planned sequence, it is possible to optimize nutrient intake, disrupt pest and disease cycles, and improve soil health. For example, leguminous crops in rotation can enhance soil nitrogen levels through BNF, reducing the need for synthetic nitrogen fertilizers [27]. Additionally, crop rotation can help balance nutrient inputs and outputs, minimizing the risk of nutrient accumulation or depletion in the soil. Diversified crop rotations lead to improved soil quality, reduced nutrient loss, and enhanced ecosystem services compared to monoculture systems [105]. Mulching is a simple yet effective practice for reducing nutrient loss from soil by conserving soil water, reducing evaporation, regulating soil temperature, minimizing weed growth, minimizing soil compaction, improving soil health, and increasing nutrient status [174]. Organic mulches, such as straw (or other crop/plant residues), hay, or compost, provide a protective layer on the soil surface, reducing the impact of rainfall and minimizing erosion [175]. In addition to erosion control, mulches contribute organic matter to the soil as they decompose, improving soil fertility and nutrient retention [176]. Some studies have shown that mulching can significantly reduce nutrient runoff and leaching, particularly in areas prone to erosion [177].

Reduced/conservation tillage offers promising opportunities for reducing nutrient loss from soil while conserving soil health and structure. Unlike conventional tillage, which involves intensive soil disturbance, conservation tillage practices minimize soil disruption, leaving crop residues on the soil surface. This protective cover reduces erosion, increases water infiltration, and enhances soil organic matter content, thereby improving nutrient retention [94]. Numerous studies have demonstrated the benefits of reduced tillage in reducing nutrient runoff and leaching, particularly in regions with vulnerable soils and high rainfall intensity [178,179].

Developing comprehensive nutrient management plans is essential for optimizing nutrient use efficiency [94] and minimizing nutrient loss from soil [180]. Soil testing plays a crucial role in nutrient management planning, providing valuable information about soil nutrient levels, pH, and texture. By analyzing soil test results, it is possible to make informed decisions regarding fertilizer types, application rates, and timing, thereby reducing the risk of nutrient overapplication and leaching [181]. Nutrient management plans also emphasize the use of best management practices, such as appropriate soil tillage nutrient split applications [182], timing fertilizer applications to coincide with crop nutrients uptake and incorporating organic amendments to improve soil fertility and structure. Numerous studies have demonstrated the effectiveness of nutrient management planning in reducing nutrient loss and improving crop yields across diverse agricultural systems [180,183].

One of the most effective strategies for reducing nutrient loss from soil is the use of CC (mostly a mixture of legume and non-legume species) [184–186]. CC are planted during fallow periods or alongside cash crops to protect the soil from erosion, retain nutrients, and improve soil health. These crops, such as legumes, grasses, and clovers, help prevent soil erosion by covering the ground surface and reducing the negative impact of rainfall. CC, such as legumes and grasses, have extensive root systems that help hold soil in place and prevent erosion. These roots also absorb excess nutrients like nitrogen, phosphorus, and potassium, which otherwise could leach into groundwater or runoff into nearby water bodies [187]. CC also contribute to overall soil health by promoting beneficial microbial activity and enhancing soil biodiversity. Healthy soils are better equipped to retain nutrients and make them available to plants, thus reducing nutrient loss [188]. CC are often used as part of crop rotation systems. Rotating cash crops with cover crops helps break pest and disease cycles, improves soil structure, and reduces nutrient imbalances, ultimately leading to better nutrient retention. In summary, CC contribute to nutrient retention in agricultural systems through various mechanisms, including nutrient uptake, erosion control, organic matter addition, weed suppression, and the overall improvement of soil health [189]. Incorporating CC into farming practices is a sustainable approach to minimize nutrient loss and promote long-term soil fertility and productivity. Several studies have demonstrated the effectiveness of CC in reducing nutrient runoff and leaching, particularly in vulnerable agricultural landscapes [190–192]. By including CC in crop rotations, it is possible to improve soil fertility, reduce nutrient loss, and promote sustainable agricultural practices.

Investigating nitrogen as one of the most important nutrients and the importance of nitrate leaching and soil tillage practices relations, Pereira et al. [193] analyze different studies (for over two decades) and conclude that the no-tillage system is in most cases dominant as a strategy in the reduction in nitrate leaching, compared to conventional tillage. They also stated that the scale of nitrate leaching depends on several factors, including soil compounds (physical, chemical, and biological) and weather conditions. According to Issaka et al. [194], the reduction in nitrogen and phosphorus losses and the improvement of soil nutrient status [41,176] can be achieved by conservation tillage and the inclusion of catch crops [19,24,173,195] and its mixture (usually crops with developed and high potential roots) for a high potential of nutrient capture [196] and effective management, especially in crop rotations [197]. CC in combination with conservation soil tillage, in most cases, has a positive influence on arable crop yields [190,193,198], without significant influences [196] or even decreased crop yields in some cases [199]. In line with the above findings, and for a better understanding of the relationships between different tillage practices and cover crops, in ways of nutrient losses from the soil, further investigations on a global level need to be performed.

4. The Influence of Cover Crops on Growth Conditions and Yield of Cereals

As was shown in the data presented in Section 3, CC used both in conservation and conventional tillage conditions may affect the biological, physical, and chemical conditions of the soil and can protect nutrients from being leached out of the reach of the cereal root system. As a result, the conditions for growth and development of cereals are improved, which often affect improved plant health status and increased grain yield (Table 1). However, this effect is very complex, and some studies indicate the opposite effect or no effect of CC on cereal yield. The results of studies concerning the effect of CC on the occurrence of cereal infection by fungal pathogens are ambiguous. Many authors have shown that under the influence of these crops, there is a significant reduction in the disease index of the succeeding cereals [44,200–202]. In some cases, no significant effect of CC on the health of cereals is observed [203], or there may be even a negative effect [204–206]. Usually, a significant reduction in the infection index, ranging from 15 to 60%, occurs as a result of the cultivation and use of white mustard and/or blue phacelia as CC [44,200–202]. In a study by Mielniczuk et al. [201], the number of colony-forming units decreased by 26% and 34% when using lacy phacelia and white mustard as CC, respectively. A weaker, although still positive effect on the cereal infection index (−4 to −10%), can be expected when using Westerwolds ryegrass [200]. In a study by Lemańczyk and Wilczewski [205], an unfavorable effect of fodder pea on the infection of roots and stem base of spring barley grown with the use of plow tillage was demonstrated. The disease index increased by as much as 60% compared to the control, without CC. However, in a study by Wojciechowski et al. [202], CC in the form of a mixture of fodder pea and field bean caused a reduction in the infection index by approx. 15%. In studies by Kwiatkowski et al. [44], a very significant (by 44.8%) reduction in the root and stem base infection index of spring wheat was demonstrated as a result of growing the legumes with an oat mixture as CC. Therefore, the effect of legumes as a CC on the health of cereals is unpredictable. More clear results regarding white mustard and lacy phacelia may be due to their beneficial effect on the development of bacteria of the genus Trichoderma, which are considered antagonistic to cereal pathogens [201]. White mustard had a particularly strong effect on the development of Trichoderma bacteria, which increased their numbers by 211%. In the case of lacy phacelia, this effect was weaker but still very significant (+98.5%). CC also contributed to a very significant increase in the numbers of other antagonists of pathogenic bacteria for cereals, e.g., Clonostachys rosea (an increase of 339% and 414% for lacy phacelia and white mustard, respectively). Taking into account the published research results, it can be stated that a reduction in the index of infection of roots and the stem base of cereals occurs both in the plowing system and in simplified systems and in direct sowing with no tillage conditions [44,200,202]. The highest average reduction in the infection index occurred under the influence of CC in reduced tillage conditions (−27.6%) and was significantly lower in plow tillage and no tillage conditions (−17.5%).

The influence of CC on weed infestation of cereals grown after them varies depending on agricultural technology, soil properties, and weather conditions during the vegetation period [44,207–210]. Kraska et al. [207] found a significant reduction in weed biomass in spring wheat cultivation. Depending on the plant species used as CC, it ranged from 10.7 to 35.7% in plow tillage conditions and from 9.2 to 30.3% in reduced tillage conditions. The greatest reduction in weed dry mass was achieved after using red clover, lacy phacelia, and white mustard as CC. Weaker effects, although significant, were provided by Westerwolds ryegrass. An even greater reduction in weed biomass was achieved in a study by Kwiatkowski et al. [44] and Darby et al. [210]. In studies by Kwiatkowski et al. [44], regardless of the tillage system, the reduction in weed biomass was about 68% in the case of lacy phacelia and 77–78% for white mustard. A slightly weaker weed control effect was found in the case of CC from the legumes with an oat mixture. These plants used as CC allowed for a reduction in weed dry mass by 40.6% in plow tillage conditions and 47.1% in conservation tillage conditions. Darby et al. [210] achieved a reduction in weed biomass in a field of spring wheat grown in the no-tillage system, from 77% in the case of millet to even 86% in the case with oats as CC. Carrera et al. [209] assumed that the lower weed biomass in CC sites was due to the delay in their germination by the biomass of plants covering the soil.

CC most often had a positive effect on the yield of cereals grown after them [48,97,209–213]. However, some studies did not show a significant effect of CC [36,214], or it was unfavorable [215,216]. The yield-forming effect of CC is also dependent on the tillage system or the plant species used as CC (Table 1). In studies on the effect of fodder radish on spring wheat yield [97], a very strong positive effect of CC was demonstrated in treatments where reduced tillage was applied (+22.6%) and a much smaller effect of this factor on grain yield occurred in plow tillage conditions (+7.2%). A very strong positive effect of oats, millet, and a mixture of oats, clover, and radish on the grain yield of spring wheat was demonstrated in no tillage conditions [210]. Also in Majchrzak's [211] studies, a significant positive effect of CC (white mustard) on the grain yield of spring wheat was found in Albic luvisol soil conditions, especially in no tillage and plow tillage treatments. The author obtained a slightly smaller, although still very positive, effect of white mustard after the use of reduced tillage. Studies on the effect of field pea, as CC, on the grain yield of spring barley also indicate the dependence of this effect on soil conditions (Table 1). In studies by Wilczewski et al. [21], a significant positive effect of this factor was demonstrated in the luvisol soil conditions, whereas in the very fertile black Earth conditions [36], with an average grain yield that was higher by 24%, this factor did not have a significant effect on the yield. These studies did not show the effect of tillage technology on the yield-forming effect of CC. In studies by Toom et al. [217], in the plow tillage system, a varied effect of individual plants used as CC was demonstrated (Table 1). A significantly positive effect on the yield of spring barley grain was demonstrated for forage radish and hairy vetch, while winter turnip rape, winter rye, and bersem clover did not significantly affect the yield of this plant. A very strong influence of the tillage system on the effect of CC in shaping the yield of winter wheat was demonstrated in a study by Wittwer et al. [212], in which white mustard and common vetch contributed to increasing the grain yield of winter wheat by 35%, while in the conditions of plow tillage, no significant effect was found, and in the conditions of no tillage it was found only after the application of common vetch. Regardless of the tillage system, the mixture of vetch and mustard did not significantly affect the yield of winter wheat. The yield-forming effect of CC, especially for winter cereals, depends on water conditions during their growth and development. According to Nielsen and Vigil [216], water use by legumes may reduce subsequent wheat yield. As a result, these authors found a reduction in grain yield of winter wheat after winter and spring pea used as CC by as much as 32.7% in comparison to the yield obtained after fallow (Table 1). Similar results were presented by Lyon et al. [215], who assessed the effect of a mixture of peas and oats on the yield of winter wheat grain.

Numerous studies on maize have shown a very positive effect of CC on grain yield, especially under reduced tillage or no tillage conditions [48,209,212,213]. In plow tillage conditions, the grain yield increase under CC was usually from 2 to 10%; however, in a study by Clark et al. [214], the increase was as much as 43.2% (Table 1). The use of CC under reduced tillage conditions resulted in an increase in the yield of maize grain by 6% and 11%, after oilseed radish and white mustard, respectively, and by 10–61% after using legumes, legume mixtures, or their mixtures with rye or white mustard for this purpose [48,209,212,213]. A positive effect of CC on maize yield was also observed under the no tillage technology [212,213].

Table 1. The influence of CC * on cereal grain yield, depending on tillage system—increase (+) or decrease (−) compared to control, without CC [%].

Cover Crops Species	Soil	Increase or Decrease [%], Depending on Tillage System			References
		Plough Tillage	Reduced	No Tillage	
		Spring wheat			
Fodder radish	Luvic chernozem	+7.2	+22.6	no data	[97]
White mustard	Albic luvisol	+18.1 to +27.6	+12.0 to + 21.5	+13.9 to +39.4	[211]
Mixture: Hairy vetch + rye	Silty Loam	+1.2 n.s. ^	no data	no data	[214]
Millet	Silty Loam	no data	no data	+71	[210]
Oat		no data	no data	+63	
Oat + clover + radish		no data	no data	+51	
		Spring barley			
Field pea	Black earth	+2.6 n.s.	+1.3 n.s.	no data	[36]

Table 1. *Cont.*

Cover Crops Species	Soil	Increase or Decrease [%], Depending on Tillage System			References
		Plough Tillage	Reduced	No Tillage	
Field pea	Luvisol	+6.3	+8.4	no data	[21]
Fodder radish	Cambic Phaeozem (Loamic)	+11.0	no data	no data	[217]
Hairy vetch		+9.0	no data	no data	
Winter turnip rape		+3 n.s.	no data	no data	
Winter rye		+3 n.s.	no data	no data	
Winter wheat					
White mustard	Cambisol	−2.3 n.s.	+30	+2.3 n.s.	[212]
Common vetch		+2.3 n.s.	+35	+7.0	
Common vetch + white mustard		+2.3 n.s.	+4.3 n.s.	+2.3 n.s.	
Field pea	Weld silt loam	−32.7	no data	no data	[216]
Oat + field pea		−29	no data	no data	[215]
Straw mulch	Claypan soil	+6.4 to +9.3	no data	n.s.	[218]
Maize (grain)					
White mustard	Cambisol	−2.0 n.s.	+11	+2.0 n.s.	[212]
Hairy vetch		+8	+61	+17	
Common vetch + white mustard		+4.0 n.s.	+45	+12	
Oilseed radish	Sandy Loam	+2.0 n.s.	+6.0 n.s.	+12	[213]
Hairy vetch	Sandy Loam	+10	+36	+19	
Subterranean clover	Sandy Loam	+9	+10.0	+14	
Hairy vetch	Sandy Acrisol	no data	+3.3 to + 15.3	no data	[48]
Hairy vetch	no information	no data	+43	no data	[209]
Mixture: Hairy vetch + rye		no data	+30	no data	
Mixture: Hairy vetch + rye	Silty Loam	+43.2	no data	no data	[214]

* CC—cover crops; ^ n.s.—not significant.

The average effect of CC on grain yield for all analyzed cereals (winter and spring wheat, spring barley, and corn) was the highest in treatments where reduced tillage was used (+23.1%), significantly lower in the no tillage conditions (+10.7%), and the lowest for plow tillage (Figure 6). Taking into account the above-mentioned negative effect of leguminous CC on the health of cereals, this positive effect on grain yield is probably caused by the fertilizing effect of the leguminous biomass. The significant amounts of N contained in their biomass and the rapid mineralization of post-harvest residues in the soil ensure good availability of N during the tillering and stem shooting period [21]. In conditions of good water supply, this leads to rapid plant growth and, consequently, greater susceptibility to fungal pathogens. Legumes are more effective than plants from other botanical groups in increasing grain yield of spring cereals. This is particularly visible in reduced tillage conditions, where mixtures with legumes showed an equally positive effect on yield as legumes in single-species cultivation. However, some studies indicate their negative effect on the grain yield of winter wheat, especially in conditions of rainfall deficiency.

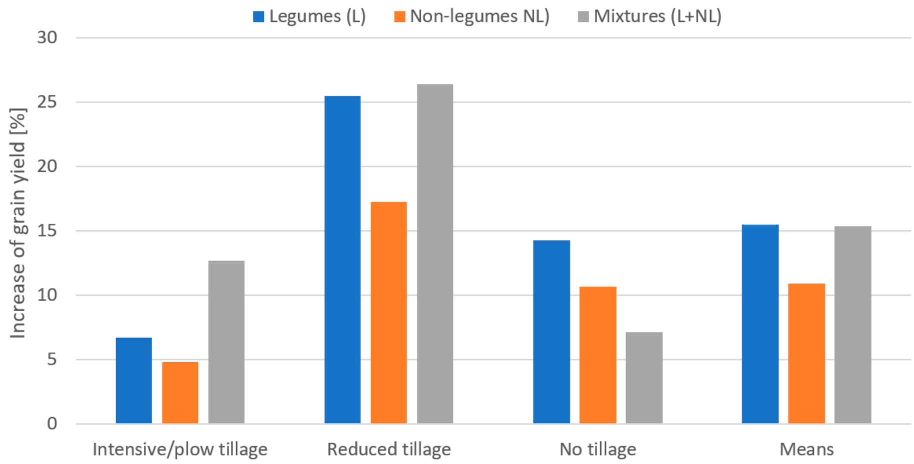

Figure 6. Average impact of plants grown as cover crops on cereals (winter and spring wheat, spring barley, and corn) grain yield, depending on tillage system [21,36,48,97,209–218].

The benefits of using CC are particularly high in conditions of low-intensity cultivation, good water supply to the main plant, and average soil conditions [21,49,212]. In a study by Acosta et al. [48], the yield-forming effect of hairy vetch as CC was 15.3% under the conditions of nitrogen fertilization at a dose of 60 kg ha^{-1} and only 3.3% for fertilization at a dose of 120 kg ha^{-1} N. In a study by Wittwer et al., [212], the inclusion of nitrogen-fixing CC in the organic production systems led to increased yields and substantially contributed to decreasing the yield gaps compared to the conventional systems. Yield differences between conventionally managed plots were reduced from −37% without CC to −19% with the use of CC mixtures.

5. Conclusions

The literature studies concerning the possibilities of shaping soil properties and cereal yields through the use of CC have shown that in the conditions of reduced tillage, they can be an important element allowing maintenance of favorable soil parameters and high plant productivity. However, it is not possible to obtain a beneficial effect of CC in all conditions. Individual plant species used as CC have a varied value in shaping soil properties as well as in terms of their influence on the growth, development, and yield of the main plant. The most studies concerned summer CC, using plants characterized by a fast growth rate (white mustard, oilseed radish, and oat), and plants with lower growth dynamics but other beneficial properties (field pea, common vetch, lupin, and serradella). Among winter CC, the most frequently used were winter rye, hairy vetch, winter turnip rape, clover, and grasses. These plants were grown both in mixtures and as a single crop.

The results presented in the current literature indicate that the influence of CC on the biological properties of soil is relatively certain. Regardless of the plant species used as CC, we can expect an increase in the number of soil microorganisms and an enrichment of their species diversity. There is also an improvement in the activity of soil enzymes (dehydrogenase, urease, and beta-glucosidase). Usually, this influence is particularly beneficial under reduced tillage systems, which are particularly conducive to the development of earthworms and other organisms belonging to the soil mesofauna, especially those from the Collembola and Acari families. CC also usually have a beneficial effect on the physical properties of the soil. However, due to the large amounts of water taken up in late summer and early autumn, they can lead to a temporary reduction in moisture and an increase in soil penetration resistance in the autumn. In early spring, they usually provide favorable physical properties for spring crops. In tillage systems that involve mixing CC biomass with the topsoil, it ensures the loosening of compacted soils and, in the case of light, sandy soils, allowing for an increase in the capacity of the sorption complex.

The influence of CC on the chemical properties of soil is less clear than its influence on the biological and physical properties. The size and composition of CC biomass and weather conditions during the vegetation period and during the covering of soil with plant biomass are of great importance for improving soil chemical properties. A beneficial influence of CC, especially legumes, on the content of the mineral nitrogen in the topsoil is usually observed. Sometimes an increase in the content of available forms of K and/or P is also achieved. The influence of CC on the content of organic C, total N, or soil pH is less common.

CC used in reduced soil tillage systems can significantly improve the yield and quality of cereal grain. The strength of this effect depends on soil conditions and the intensity of agricultural technology. The greatest positive effect on cereal yield is obtained as a result of using legumes as CC, in conditions of less fertile soils, and in conditions of low fertilization levels. In these conditions, we can expect an increase in the grain yield by 15–25% and sometimes even by over 40%. The improvement in yield is mainly related to the more dynamic development of plants, increased numbers of spikes, and the number of grains in the cereal spike. In average soil conditions, the increase in cereal yield is in the range of 5–15%, and in the case of fertile soils and/or the use of full N fertilization, no direct effect of CC on grain yield is observed.

Author Contributions: Conceptualization, E.W., M.S. and E.S.-K.; methodology, E.W., E.S.-K. and M.S.; investigation, E.W., I.J., E.S.-K., M.S. and D.J.; data curation—results compiled and analyzed, E.W., I.J., E.S.-K., M.S. and D.J.; writing—original draft preparation, E.W., I.J., E.S.-K., M.S. and D.J.; review and editing, E.W. All authors have read and agreed to the published version of the manuscript.

Funding: This study has been partly supported by the Croatian Science Foundation under the project "Assessment of conservation soil tillage as advanced methods for crop production and prevention of soil degradation—ACTIVEsoil" (IP-2020-02-2647).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

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