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The Effect of Long-Term Crop Rotations for the Soil Carbon Sequestration Rate Potential and Cereal Yield

Lina Skinulienė *, Aušra Marcinkevičienė, Mindaugas Dorelis and Vaclovas Bogužas

Department of Agroecosystems and Soil Sciences, Agriculture Academy, Vytautas Magnus University, K. Donelaičio Str. 58, LT-44248 Kaunas, Lithuania; ausra.marcinkeviciene@vdu.lt (A.M.); mindaugas.dorelis@vdu.lt (M.D.); vaclovas.boguzas@vdu.lt (V.B.)

* Correspondence: lina.skinuliene@vdu.lt; Tel.: +370-674-12525

Abstract: Depending on the type of agricultural use and applied crop rotation, soil organic carbon accumulation may depend, which can lead to less CO_2 fixation in the global carbon cycle. Less is known about organic carbon emissions in different crop production systems (cereals, grasses) using different agrotechnologies. There is a lack of more detailed studies on the influence of carbon content in the soil on plant productivity, as well as the links between the physical properties of the soil and the absorption, viability, and emission of greenhouse gases (GHG) from mineral fertilizers. The aim of this study is to estimate the long-term effect of soil organic carbon sequestration potential in different crop rotations. The greatest potential for organic carbon sequestration is Norfolk-type crop rotation, where crops that reduce soil fertility are replaced by crops that increase soil fertility every year. Soil carbon sequestration potential was significantly higher (46.72%) compared with continuous black fallow and significantly higher from 27.70 to 14.19% compared with field with row crops and cereal crop rotations, respectively, intensive crop rotation saturated with intermediate crops. In terms of carbon sequestration, it is most effective to keep perennial grasses for one year while the soil is still full of undecomposed cereal straw from the previous crop. Black fallow without manure fertilization, compared to crop rotation, reduces the amount of organic carbon in the soil up to two times, the carbon management index by 2–5 times, and poses the greatest risk to the potential of carbon sequestration in agriculture.

Keywords: carbon sequestration rate; carbon management index; soil organic stock

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1. Introduction

Plants have the ability to take carbon dioxide (CO_2) from the atmosphere and incorporate it into their own biomass through the process of photosynthesis. The storage of carbon in the form of living biomass is considered a technique for short-term carbon sequestration, whereas the sequestration of carbon in soil organic carbon (SOC) is seen as a long-term strategy. Over the next 50–100 years, applying appropriate agriculture practices might sequester 80–130 GT (10^9) carbon as SOC. Carbon, as the predominant elemental constituent of soil organic matter, exerts a substantial influence on the physical, chemical, and biological characteristics of soil, hence impacting the productivity of soil biomass. Carbon sequestration offers a multitude of ancillary advantages, encompassing the mitigation of climate change, enhancement of ecosystem health, promotion of food security, and facilitation of agricultural profitability [1].

The global carbon (C) cycle is of utmost importance in the efforts to mitigate climate change. A key aspect of this process involves the capacity of vascular plants to uptake atmospheric carbon dioxide (CO_2) and incorporate it into their systems through the process of photosynthesis [2]. Soil organic carbon (SOC) plays a crucial role in the global carbon cycle, as the highest layers of soil are believed to possess around three times the amount of carbon present in the entire atmosphere [3]. It is imperative to ensure that the soil organic carbon (SOC) levels in the root zone remain above the designated threshold of 1.5–2.0% in order to preserve the proper functioning of diverse soil processes [1,4].

Soil organic matter serves as the fundamental constituent that facilitates the cohesion of primary soil particles, leading to the formation of micro- and macro-aggregates and contributing to the overall structural integrity of the soil. Additionally, it serves as a storage facility for keeping moisture and nutrients, enhancing the ability of soils to endure periods of drought, minimizing nutrient losses, and improving the efficiency of fertilizer and waste utilization. Organic matter has a significant role as an essential energy source for soil microbes, hence augmenting their functional and genomic biodiversity, which is of utmost importance for maintaining soil biological health [5].

Soil carbon sequestration offers various other advantages, encompassing enhanced ecological well-being, bolstered food security, and increased agricultural profitability. The implementation and promotion of site-specific sustainable farming practices, such as conservation tillage and cover cropping, have the potential to enhance both crop and pasture productivity while simultaneously mitigating soil carbon losses [1,6].

The capacity for SOC (soil organic carbon) sequestration is influenced by both soil type and tillage management practices. The reaction of the soil organic carbon (SOC) to the implementation of cover cropping or diversified crop rotation was shown to be more pronounced in soils with a medium texture compared to other soil types. The production of plant biomass, ground covering, and the input of biomass carbon (C) into the soil are constrained by weather conditions, leading to a deficit of carbon in soils [7–9].

In order to increase the amount of organic carbon in the soil, one way to achieve this is through crop rotation. Scientists have found that well-chosen crop rotation effectively improves crop resilience to climate change, water dynamics, soil health, and biological conditions [10]. Bowles et al. [10] confirm the conclusions of other scientists with their research and, at the same time, add additional benefits of crop rotation, such as effective control of weeds and pathogens, higher crop productivity, and better economic benefits. At the same time, the risks of weather extremes are reduced [11].

By increasing the amount of organic matter in the soil, the task of sustainable agriculture is to ensure the long-term and stable productivity of crops by reducing the need for mineral fertilizers and irrigation [12]. In order to determine how different agricultural practices affect the soil, CSR and CMI indicators are calculated.

The carbon sequestration rate (CSR) is evaluated in modeling and improving agricultural systems to improve soil health. In order to minimize the threat to soil productivity, additional crops, tillage changes, etc. are added, and at the same time, modeling processes are developed for how the input will change the soil several years into the future. However, such modeling processes are not always useful because the absorption of certain processes is influenced by the region, soil type, and prevailing climatic conditions [13]. The carbon management index (CMI) is the indicator that is most responsive to changes in agricultural conditions [14].

Chahal et al. [15] emphasized the need to focus on research that reflects the relationship between soil health and plant productivity in evaluating all agricultural practices.

The aim of this study is to estimate the long-term effect of soil organic carbon sequestration potential on different crop rotations and cereal productivity.

2. Materials and Methods

2.1. Experiment Design and Agricultural Practices

A long-term experiment (collection of crop rotations) was initiated in 1967 by Prof. A. Stancevičius at Vytautas Magnus University Experimental Station (54°53′ N, 23°50′ E) and has been continued until now (Figure 1) [16].

Figure 1. The long-term field experiment conducted at Vytautas Magnus University, Kaunas, Lithuania (54°53′ N, 23°50′ E), (aut. Mindaugas Dorelis).

In the field experiment, there are a total of 58 combinations of crop rotation plots, with a harvested plot area of 18 m long by 9.60 m wide. Three iterations were applied. Crop rotations are arranged in the field, and over time, 15 varieties of agricultural crops are grown each year. The study was conducted in 7 different crop rotations: intensive, three-course, field rotation with row crops for green manure, Norfolk, cereal, fodder, and rye monoculture, and continuous bare fallow as well. The research was performed on spring barley, winter wheat, and winter rye (Table 1). All soil samples were taken before harvesting from fields with the main cereal. The treatments that were selected had different pre-crops (Table 1). All components of crop rotation are listed in Appendix A.

Table 1. Crop rotations with different pre-crops.

Crop Rotation	Main Crop	Pre-Crop
Intensive (INT)	spring barley (*Hordeum vulgare* L.) "Orhelija" (180 kg ha^{-1})	Corn
Cereal (CE)		Vetch and oats mixture for green forage
Field with row crops (FWR)		Sugar beet
Norfolk (NOR)		Potatoes
Fodder (FOD)		Fodder beet
For green manure (FGM)		Potatoes
Cereal (CE)	winter wheat (*Triticum aestivum* L.) "Skagen" (200 kg ha^{-1})	Oats
Field with row crops (FWR)		Black fallow
Norfolk (NOR)		Clover–timothy mixture
Intensive (INT)	winter rye (*Secale cereal* L.) "Matador" (180 kg ha^{-1})	Potatoes
Rye monoculture (MONO)		Rye monoculture
Three-course (TC)		Black fallow
Field with row crops (FWR)		Perennial grasses (second year)
For green manure (FGM)		Winter rape
Continuous black fallow (FAL)		

The crop rotations differ not only in crop sequences but also in specific organic matter input and type (shoot, root litter, and cattle manure) (Table 2). In all crop rotations, straw is retained and incorporated into the soil as organic fertilizer. Undersowing is sown: into wheat in field crop rotations with row crops; into a vetch–oat mixture in cereal crop rotations. Cattle manure (55 t ha^{-1}) was applied for winter cereals in the fields of field crop rotation with row crops and Norfolk crop rotations. Organic fertilizers were incorporated by plowing in at a depth of 20–25 cm [16].

Table 2. Sources of organic matter in crop rotations.

Crop Rotations	Crops	Organic Matter (t ha^{-1})			
		Manure	Straw	Green Manure	Perennial Grasses
Intensive (INT)	Spring barley		5.04	39.20	
	Winter rye	55.00	3.54	19.80	17.80
Rye monoculture (MONO)	Winter rye		3.89		
Three-course (TR)	Winter rye		4.10		
Cereal (CE)	Spring barley		4.07		
	Winter wheat	55.00	7.76		
Field with row crops (FWR)	Spring barley		4.76		
	Winter rye	55.00	3.57		2.80
	Winter wheat		7.13		
Fodder (FOD)	Spring barley		4.52		
Norfolk (NOR)	Spring barley		3.38		
	Winter wheat	55.00	6.38		32.00
For green manure (FGM)	Winter rye		3.68	19.50	
	Spring barley		4.35		

The soil of the experimental site is *Endocalcari-Epihypogleyic Cambisol* (sicco) (CMg-p-w-can) [17].

Granulometric composition is as follows: dusty loam on loam and clay. Average nutrient contents in the soil analyzed (data for 2014, 2015, and 2016): pH—from 6.6 to 7.0; P_2O_5—from 131 to 206.7 mg kg^{-1}; K_2O—from 72.0 to 126.9 mg kg^{-1}.

During the experiment, the same arable tillage system was implemented, and plant protection products were used as needed.

The soil agrochemical properties of the experimental sites were determined before the establishment of the field trial and in each experimental year. By using a soil auger, samples were collected from the plough layer at a depth of 0–25 cm from 15 spots in each plot. Then, the samples were composited (250 g per sample) to provide a representative plot sample for each depth. Organic carbon was measured using a spectrophotometric method. The quantity of nitrogen per mg kg^{-1} soil was measured using the Kjeldahl method (%), while the contents of phosphorus and potassium were measured using the A–L (Egner–Riehm–Domingo) method [18].

The cereal yield was measured at the time of harvesting with a Wintersteiger harvester equipped with a weighing and moisture determination system. The grain yield (t ha^{-1}) was adjusted to the standard of 14% moisture and 100% purity [18].

2.2. Meteorological Conditions

In 2021, August was cooler and wetter than normal. September and October were drier than normal. November and December were warmer than normal, and precipitation was close to the long-term normal (Table 3).

In 2022, January and December were warmer, and March and April were colder than normal. March had almost no precipitation. Vegetation resumed on 9 April. May was cold and wet. June was warmer and July was colder than normal. August was unusually hot and dry. September was colder than usual, while October, November, and December were warmer than usual.

Table 3. Meteorological conditions during the experimental period, Kaunas Weather Station.

Year/Month	January	February	March	April	May	June	July	August	September	October	November	December
Average air temperature (°C)												
2020	2.5	2.2	3.6	6.9	10.5	19.0	17.4	18.7	14.9	10.3	5.2	0.6
2021	−3.5	−5.0	1.7	6.2	11.4	19.5	22.6	16.5	11.6	8.1	4.2	−2.3
2022	0.02	1.4	1.7	6.2	11.0	17.7	17.9	20.9	11.1	10.2	2.9	−2.5
Long-term average	−3.7	−4.7	0.3	6.9	13.2	16.1	18.7	17.3	12.6	6.8	2.8	−2.8
Precipitation rate (mm)												
2020	52.8	54.9	29.3	4.0	94.4	99.3	60.4	92.8	13.3	52.5	30.0	17.1
2021	82.2	12.3	22.0	33.7	121.6	40.3	48.4	122.2	29.1	27.2	55.5	38.0
2022	69.0	73.7	3.60	38.4	84.0	77.6	100.5	38.7	26.0	17.7	30.7	44.1
Long-term average	38.1	35.1	37.2	41.3	61.7	76.9	96.6	88.9	60.0	51.0	51.0	41.9

2.3. The Computation of Carbon Sequestration Potential

Soil organic carbon stock (SOC stock) was counted according to the following equation:

$$\text{SOC stock (Mg ha}^{-1}\text{) = SOC (g kg}^{-1}\text{)} \times \text{soil bulk density (Mg m}^{-3}\text{)} \times \text{layer depth (m)} \times 10 \quad (1)$$

The difference in carbon sequestration at 0–25 cm depth was determined from a specific crop rotation SOC stock in spring barley, winter wheat, and winter rye crops, subtracting the SOC stock of continuous black fallow. Soil carbon sequestration rate (CSR) in one year was as follows: the aforementioned differences in C sequestration were calculated by dividing by the number of years of the field experiment according to the following equation [19]:

$$\text{CSR (kg C ha}^{-1}\text{ m}^{-1}\text{)} = \frac{\text{C stock (CR)} - \text{C stock (FAL)}}{\text{Time (yr)}} \times 1000 \quad (2)$$

where C stock (CR) = specific crop rotation C stocks in spring barley, winter wheat or winter rye crops;

C stock (FAL) = C stocks in continuous black fallow;

1000 = coefficient for recount per kg.

Time (yr) = 52

Soil carbon management index (CMI) is estimated following the Blair and etc. [20] method:

$$\text{CMI = Carbon pool index (CPI)} \times \text{Lability index (LI)} \times 100 \quad (3)$$

where

$$\text{CPI} = \frac{\text{Overall C quantity in investigated soil}}{\text{Overall C quantity in control (FAL)}} \quad (4)$$

$$\text{LI} = \frac{\text{C mobility in the tested soil}}{\text{C mobility in the soil of the control (FAL)}} \quad (5)$$

where C mobility is the ratio of the accumulation of mobile humic substances to the accumulation of C insoluble residue.

The mobile humic substance stock (MHS) is estimated using the following formula:

$$\text{MHS} = \text{JHM (mobile humic substance)} \times \text{soil bulk density (Mg m}^{-3}\text{)} \times \text{layer depth (m)} \times 10 \quad (6)$$

2.4. Statistical Analysis

The research data were processed by the method of analysis of variance using the computer program SYSTAT 12 (Armonk, NY, USA). The research data were statistically evaluated by the method of one-way analysis of variance (ANOVA) of quantitative traits as well as the LSD test [21,22].

3. Results

3.1. Soil Organic Carbon Sequestration Potential in Different Crop Rotations

Soil carbon sequestration potential is reflected by differences in carbon sequestration rate (CSR) compared to unfertilized continuous black fallow and carbon management index (CMI). These indicators were determined in different crop rotations after 52 years of field experimentation.

After spring barley harvest, the lowest C management index was determined in continuous black fallow and for green manure (FGM) crop rotation after potato as pre-crop, 21.02 and 35.28%, respectively (Figure 2). CMI was significantly higher in cereal, fields with row crops, Norfolk, and intensive crop rotations (respectively after oats, sugar beets, potatoes, and corn). Comparing these crop rotations with fodder crop rotations, CMI was higher and more sought, ranging from 35.28 to 60.90%. The explanation for this result could be that perennial grasses are used for four years, which is 50% of all fodder crop rotation.

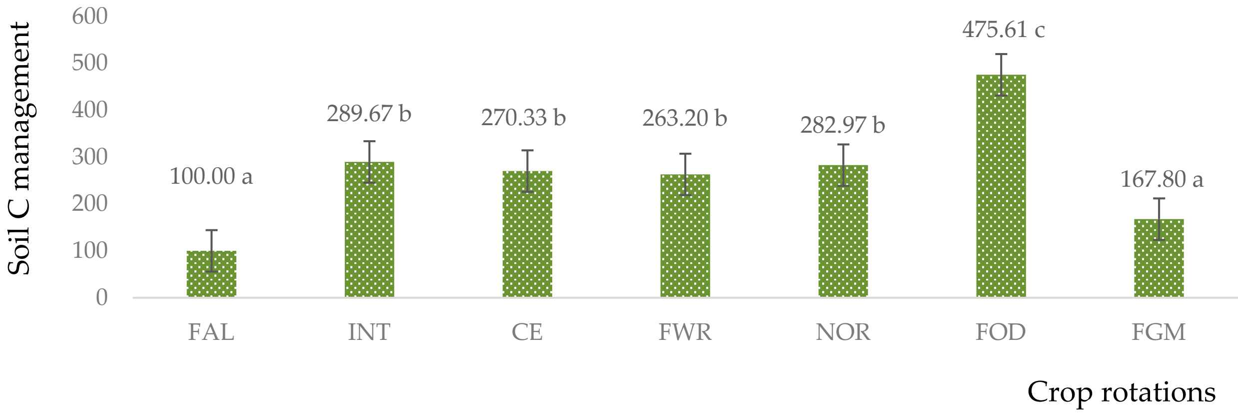

Figure 2. Effect of long-term soil C management index at 25 cm depth in spring barley after 52 years. FAL—continuous black fallow; INT—intensive crop rotation; CE—cereal crop rotation; FWR—field with row crop rotation; FOD—fodder crop rotation; NOR—Norfolk crop rotation; FGM—for green manure crop rotation. Different letters indicate significant differences between the treatments (a, b, c). Differences are significant ($p < 0.05$). The bars display a standard error.

For these reasons, mobile humic substances are found here twice as much as in other crop rotations, and this determined the high C management index of the fodder crop rotation. Meanwhile, in the continuous black fallow, which was not fertilized with manure, mobile humic substances were almost four times less compared to the fodder crop rotation.

The differences in soil sequestration rate were also huge when comparing crop rotations in spring barley crops (Figure 3). The lowest CSR was established for green manure crop rotation—231 kg C ha^{-1} per year.

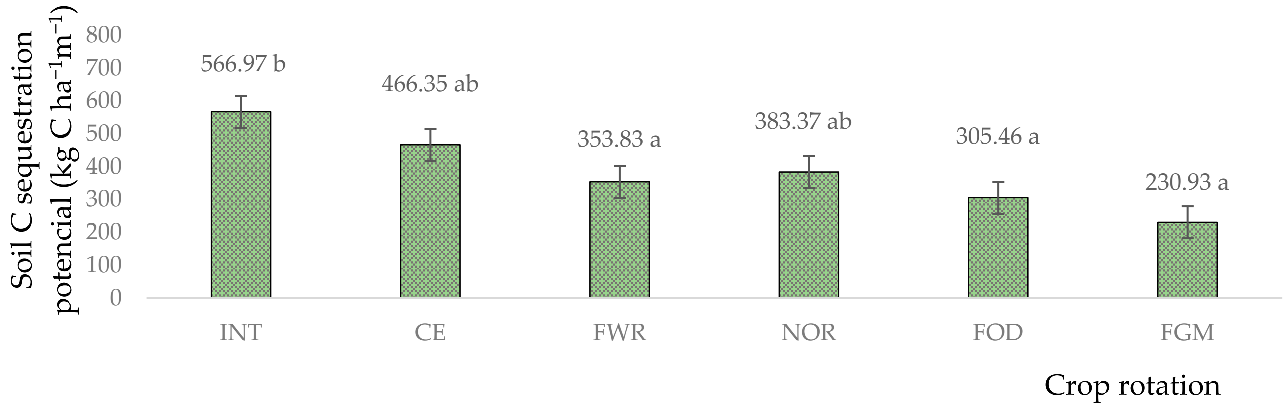

Figure 3. Effect of long-term soil C sequestration potential at 25 cm depth in spring barley after 52 years. INT—intensive crop rotation; CE—cereal crop rotation; FWR—field with row crop rotation; FOD—fodder crop rotation; NOR—Norfolk crop rotation; FGM—for green manure crop rotation. Different letters indicate significant differences between the treatments (a, b). Differences are significant ($p < 0.05$). The bars display a standard error.

This result could be explained by the fact that C/N was the lowest as well. The soil sequestration rate was established to be very comparable in fields with row crop and fodder crop rotations. This indicator was significantly higher in intensive crop rotation (567 kg C ha^{-1} per year) compared with other crop rotations. CSR was established at 383 and 466 kg C ha^{-1} per year, respectively, in Norfolk and cereal crop rotations compared with other crop rotations, and there were no significant differences.

The highest soil carbon stock was established in intensive, cereal, Norfolk, and field row crops, ranging from 42.24 to 31.34% compared with continuous black fallow (Figure 4). A huge indicator of mobile humic substance stock (MHS) was in intensive, cereal, field with row crops, and Norfolk crop rotation, and it was significantly higher from 62.72 to 58.35% compared with continuous black fallow, but the significantly highest 72.84% MHS was in fodder crop rotation; half of this crop rotation included perennial grasses.

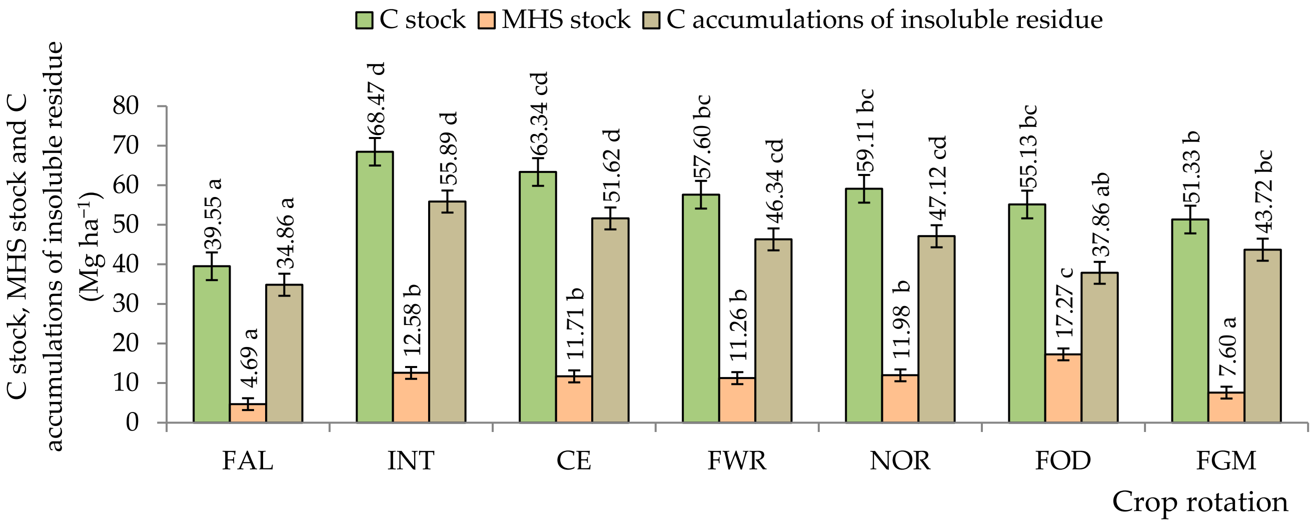

Figure 4. Effect of long-term soil C stock, MHS stock, and C accumulations of insoluble residue at 25 cm depth in spring barley after 52 years. FAL—continuous black fallow; INT—intensive crop rotation; CE—cereal crop rotation; FWR—field with row crop rotation; FOD—fodder crop rotation; NOR—Norfolk crop rotation; FGM—for green manure crop rotation. Different letters indicate significant differences between the treatments (a, b, c, d). Differences are significant ($p < 0.05$). The bars display a standard error.

The accumulations of insoluble residue indicators were significantly lower in continuous black fallow, ranging from 37.63 to 7.93% compared with all investigated crop rotations.

The significant differences in soil carbon management index were established in winter wheat crops as well. The highest CMI (371.08) was established in Norfolk crop rotation, where the primary crop of winter wheat was perennial grasses, which leave a lot of plant residues with a huge amount of nitrogen (Figure 5). CMI was significantly higher, from 23.58 to 34.80%, respectively, in fields with row crops and cereal crop rotations compared with continuous black fallow.

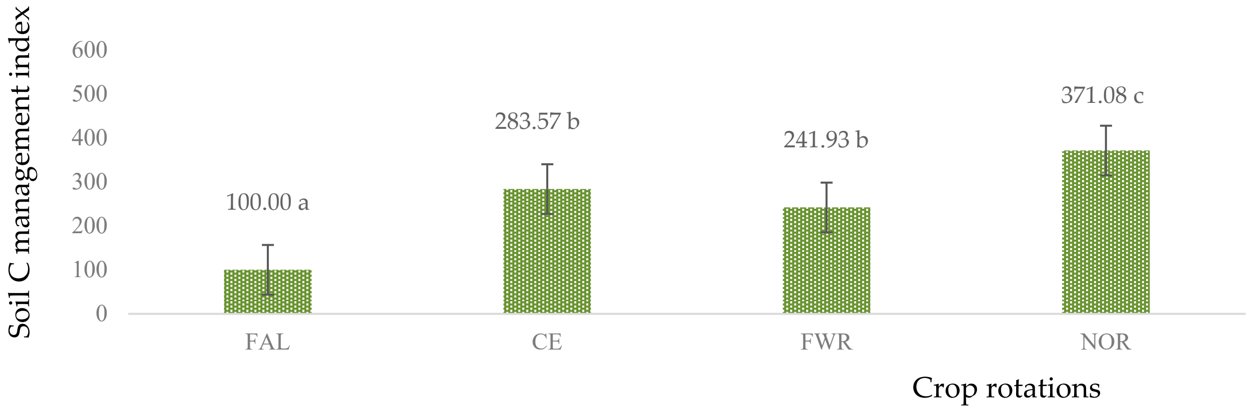

Figure 5. Effect of long-term soil C management index in 25 cm depth on winter wheat after 52 years. FAL—continuous black fallow; CE—cereal crop rotation; FWR—field with row crop rotation; NOR—Norfolk crop rotation. Different letters indicate significant differences between the treatments (a, b, c). Differences are significant ($p < 0.05$). The bars display a standard error.

The primary crops in these crop rotations were black fallow not fertilized by manure and a vetch–oat mixture for fodder, respectively.

The highest soil carbon sequestration rate was established in Norfolk crop rotation after first-year perennial grasses, and it was even 680 kg C ha^{-1} per year (Figure 6). This indicator was significantly lower in the cereal crop rotation and aimed at 474. The primary crop of the cereal crop rotation was a vetch and oat mixture.

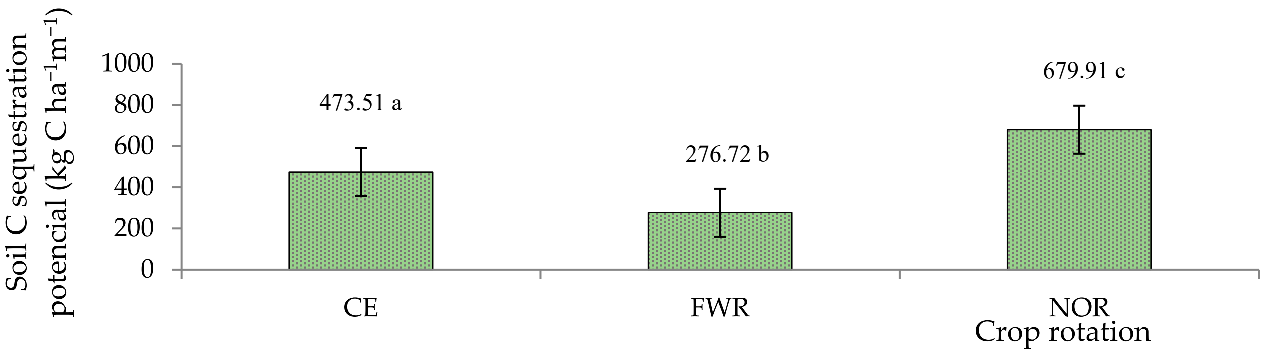

Figure 6. Effect of long-term soil C sequestration potential in 25 cm depth on winter wheat after 52 years. CE—cereal crop rotation; FWR—field with row crop rotation; NOR—Norfolk crop rotation. Different letters indicate significant differences between the treatments (a, b, c). Differences are significant ($p < 0.05$). The bars display a standard error.

In relation to soil sequestration rate, the most effective primary crop is perennial grasses, while a lot of straw is in the soil. The significantly lower soil sequestration rate was in the winter wheat crop after black fallow and aimed at just 277 kg C ha^{-1} per year.

The most effective primary crop for soil chemical properties was perennials grasses in winter wheat cereal, because the highest amount of soil carbon stock was established in Norfolk crop rotation, and it was significantly higher (46.72%) compared with continuous black fallow and significantly higher from 27.70 to 14.19% compared with field with row crops and cereal crop rotations, respectively (Figure 7).

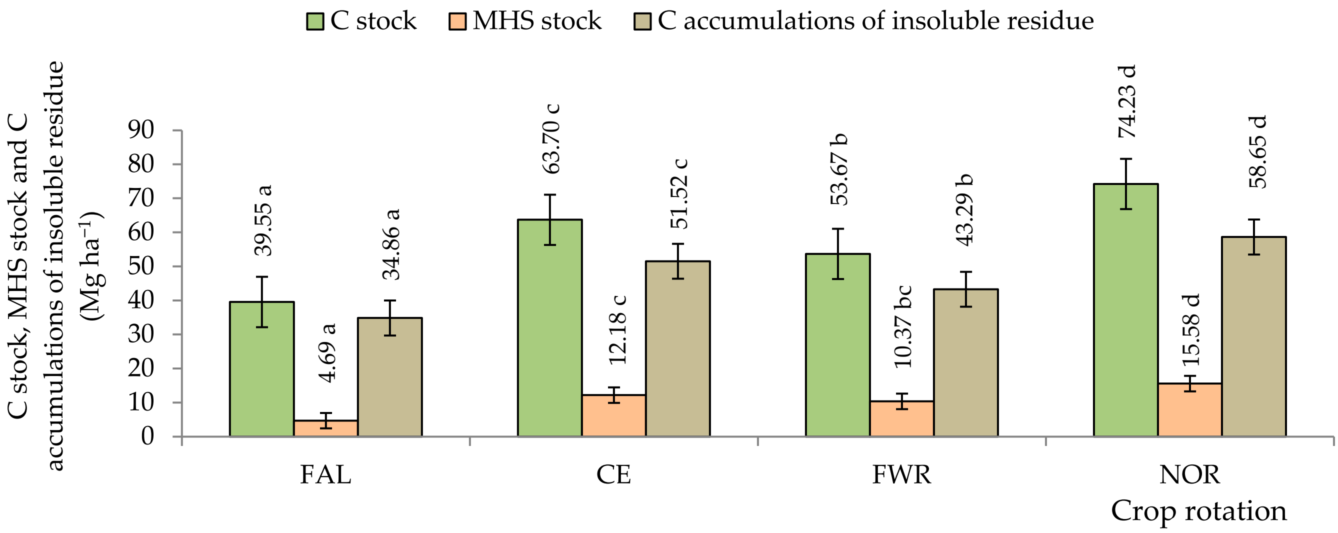

Figure 7. Effect of long-term soil C stock, MHS stock, and C accumulations of insoluble residue in 25 cm depth in winter wheat after 52 years. FAL—continuous black fallow; CE—cereal crop rotation; FWR—field with row crop rotation; NOR—Norfolk crop rotation. Different letters indicate significant differences between the treatments (a, b, c, d). Differences are significant ($p < 0.05$). The bars display a standard error.

The proportional results of MHS stocks and C accumulations of insoluble residues were established as C stocks.

After the harvest of winter rye, the lowest soil carbon management index was established in continuous black fallow that was not fertilized by manure (Figure 8).

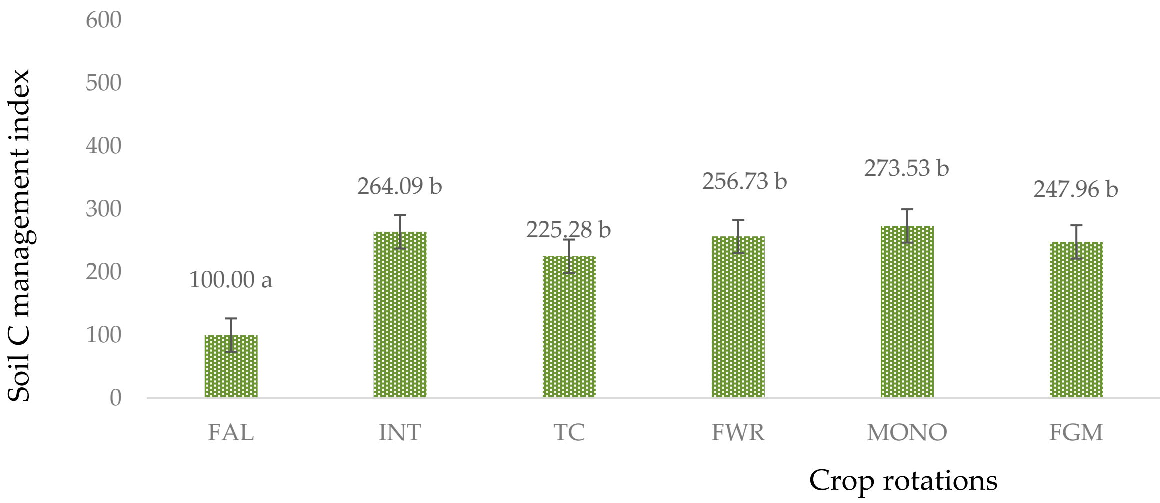

Figure 8. Effect of long-term soil C management index in 25 cm depth on winter rye after 52 years. FAL—continuous black fallow; INT—intensive crop rotation; MONO—winter rye monoculture; TC—three-course crop rotation; FWR—field with row crop rotation; FGM—for green manure crop rotation. Different letters indicate significant differences between the treatments (a, b). Differences are significant ($p < 0.05$). The bars display a standard error.

The effect of crop rotations compared with continuous black fallow was significantly higher. However, when comparing crop rotations with each other, significant differences were not established.

The CMI ranged from 30.3 to 36.8. The differences in soil carbon sequestration rate were not significant when compared to crop rotations (Figure 9). This indicator ranges from 319 (winter rye monoculture) to 442 (after winter rape incorporated as green manure in soil) kg C ha^{-1} per year.

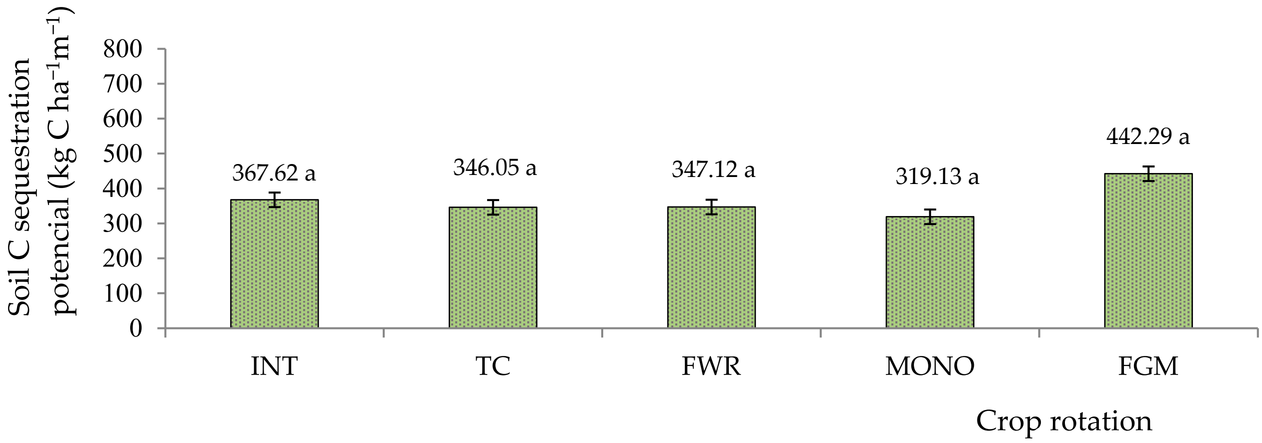

Figure 9. Effect of long-term soil C sequestration potential in 25 cm depth on winter wheat after 52 years. INT—intensive crop rotation; MONO—winter rye monoculture; TC—three-course crop rotation; FWR—field with row crop rotation; FGM—for green manure crop rotation. The same letters indicate no significant differences between the treatments (a). Differences are not significant ($p > 0.05$). The bars display a standard error.

The highest results of C stocks, MHS stocks, and C accumulations of insoluble residue were in crop rotations where primary crops leave a huge amount of residue. Significantly higher, from 36.35 to 32.16%, C stocks were established for green manure and intensive crop rotations where primary crops were winter rape incorporated in soil and perennial grasses, respectively, compared with continuous black fallow (Figure 10).

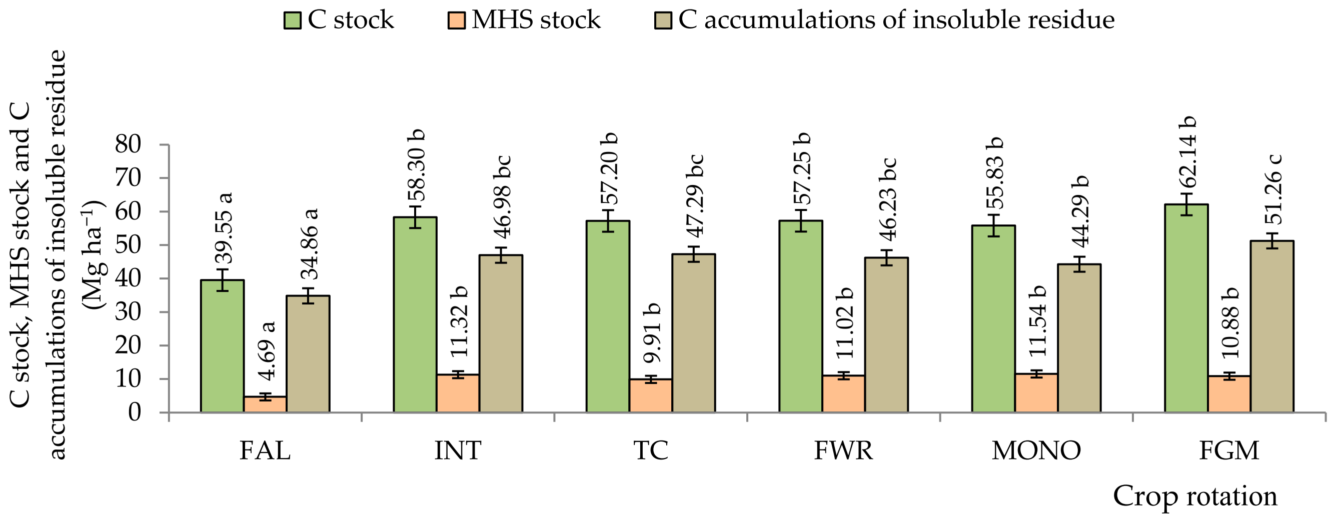

Figure 10. Effect of long-term soil C stock, MHS stock, and C accumulations of insoluble residue in 25 cm depth on winter rye after 52 years. FAL—continuous black fallow; INT—intensive crop rotation; MONO—winter rye monoculture; TC—three-course crop rotation; FWR—field with row crop rotation; FGM—for green manure crop rotation. Different letters indicate significant differences between the treatments (a, b, c). Differences are significant ($p < 0.05$). The bars display a standard error.

The significantly higher MHS stocks, from 58.57 to 57.44%, were established in intensive and field crop rotations, respectively. The pre-crops of winter rye in both crop rotations were perennial grasses.

3.2. Cereal Productivity

Crop productivity was evaluated in the 2022 year. The significantly higher spring barley cereal yield, from 33.52 to 29.77%, was established in cereal and fooder crop rotations. The primary crop was oats and fodder beet fertilized manure, respectively, coexisting with field and row crop rotations (Figure 11).

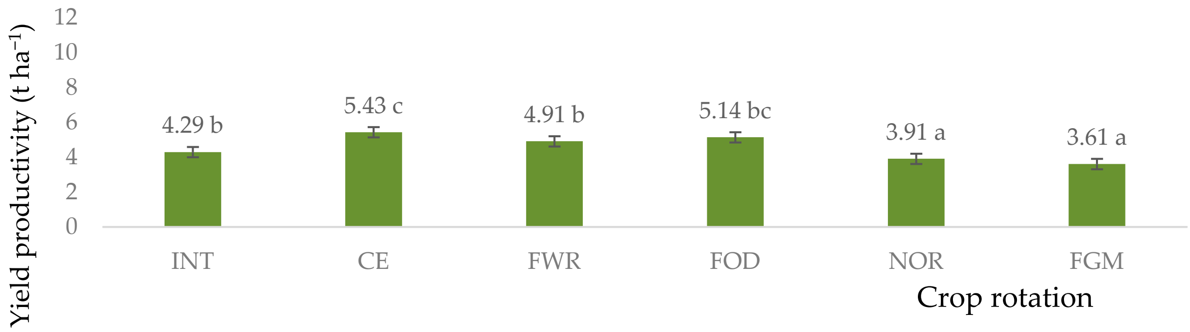

Figure 11. Spring barley productivity after various pre-crops in different crop rotations in 2022. INT—intensive crop rotation; CE—cereal crop rotation; FWR—field with row crop rotation; FOD—fodder crop rotation; NOR—Norfolk crop rotation; FGM—for green manure crop rotation. Different letters indicate significant differences between the treatments (a, b, c). Differences are significant ($p < 0.05$). The bars display a standard error.

The lowest yield was established in fields with row crop rotations, and it would be affected by pre-crops, which were sugar beets.

Winter wheat yield productivity was significantly higher in cereal (20.50%) crop rotation and field with row crops (17.89%) compared with Norfolk crop rotation (Figure 12).

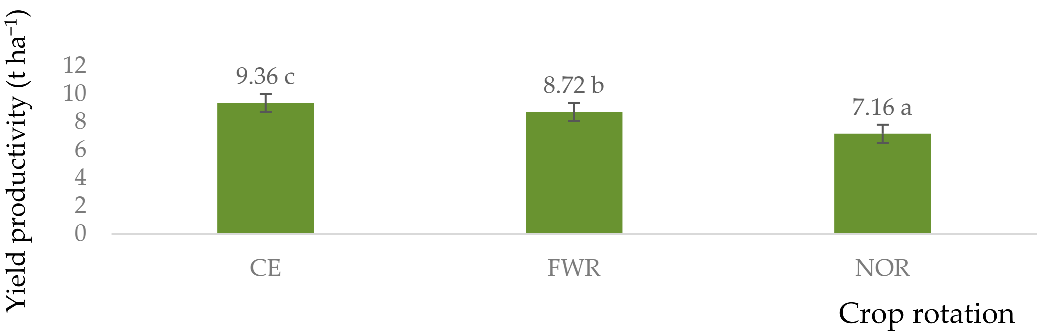

Figure 12. Winter wheat productivity after various pre-crops in different crop rotations in 2022. CE—cereal crop rotation; FWR—field with row crop rotation; NOR—Norfolk crop rotation. Different letters indicate significant differences between the treatments (a, b, c). Differences are significant ($p < 0.05$). The bars display a standard error.

Pre-crop of winter wheat in cereal crop rotation was a vetch and oats mixture, field with row crops—black fallown, Norfolk—first-year perennial grasses.

The best primary crop for winter rye yield was second-year perennial grasses in fields with row crop rotation, and it was significantly higher at 10.30% compared with green manure crop rotation and 9.47% compared with intensive crop rotation (Figure 13).

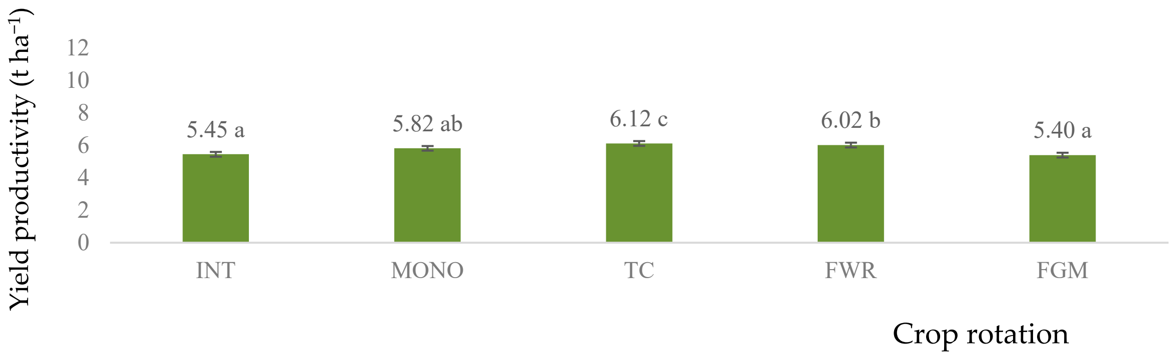

Figure 13. Winter rye productivity after various pre-crops in different crop rotations in 2022. INT—intensive crop rotation; MONO—winter rye monoculture; TC—three-course crop rotation; FWR—field with row crop rotation; FGM—for green manure crop rotation. Different letters indicate significant differences between the treatments (a, b, c). Differences are significant ($p < 0.05$). The bars display a standard error.

4. Discussion

Zani et al. [23] found that an effective way to increase soil carbon sequestration is to include clover and other herbaceous plants in the crop rotation for several years. The results showed that the soil was enriched with organic compounds after 3 years of herbaceous plants in the rotation, but the highest levels were found in the subsoil. The average organic carbon stocks in crops grown on mineral soils were 61 ± 25 and 62 ± 25 Mg ha^{-1} in 0–30 cm (topsoil) and 35 ± 30 and 44 ± 28 Mg ha^{-1} in 30–100 cm (subsoil). In contrast, perennial grassland accumulated significantly more SOC (88 ± 32 and 47 ± 50 Mg ha^{-1} in topsoil and subsoil, respectively). In total, 67 ± 14% and 33 ± 14% of the total SOC stocks were accumulated in topsoil and subsoil, respectively [24]. Long-term experiments and evaluation of the results have shown that intensification of the agricultural system, deep plowing, and the absence of cover crops rapidly reduce the SOC content, while crop residues and manure application increase the SOC levels in the soil [25]. Jacobs et al. [26] estimated organic carbon levels and found that, on average, there was no difference in total Corg content between plowed soils (3.7 ± 1.8 Mg ha^{-1} y^{-1}) and grassland soils (3.7 ± 1.3 Mg ha^{-1} y^{-1}). Moreover, there was a difference in the organic residues themselves, which are the source of Corg: grassland soils had 1.4 times more Corg from the roots of the plants than plowed crops. It is the quality, not the quantity, of organic residues that accounts for the difference in soil Corg stocks between tillage practices. Fields with cover crops would accumulate 0.28–0.33 Mg C ha^{-1} a^{-1} over 50 years [27]. Prudil et al. [28] found that crop residues and the additional input of organic residues into the soil mainly influenced carbon stocks. The projection showed that soil carbon stocks decreased with monoculture. The results also confirmed that straw incorporation and cover crops maintain a stable and gradually increasing soil carbon stock under all modeled climate scenarios. SOC stocks at the end of the century were around 66 t/ha. This implies an average SOC sequestration of about 0.09 t/ha/year.

The rate of carbon sequestration, after changing CT to NT, is expected to peak in 5–10 years, and SOC is expected to reach a new equilibrium in 15–20 years. By increasing the complexity of rotation, SOC can reach a new equilibrium in about 40–60 years [29].

R. Lal [30] pointed out that soil C accumulation is a win-win situation as it also increases crop yields and helps to increase global food security. On the other hand, it is difficult to quantify the role of SOM in increasing crop productivity and ensuring the stability of agricultural production. The Chahal et al. [15] study shows that intercropping cereals (winter wheat, oats, and barley) with cover crops (red clover) and/or perennial crops (alfalfa) improves soil condition and increases crop productivity. The obtained results confirmed the synergistic benefits of crop rotation diversification on soil quality and crop productivity in the long term. Our long-term research shows the profit of perennial grasses and manure incorporation in crop rotation. For this reason, C sequestration rate potential and C stock are the highest in the Norfolk crop rotation compared with other crop rotations. After 52 years of research, we can say that organic matter is the best soil biological, chemical, and physical improver. Furthermore, the highest CMI (475.61) was established in the fodder crop rotation, and compared with other crop rotations, the difference was from 35.28 to 60.90% in spring barley crops. There are four years of perennial grasses in this crop rotation, and it is the most sustainable management system compared with other crop rotations. Investigating soil properties in winter wheat crops in different crop rotations, the highest profit was established in the Norfolk crop rotation, where the pre-crop was perennial grasses and the differences in CMI were from 65.20 to 76.42% compared with other crop rotations. The results showed the lowest (225.28) CMI among those growing just cereal and established black fallow, evaluating the influence of different crop rotations on soil in winter rye crops. An agricultural system with a CMI value above 100 is considered a sustainable management system. However, Blair et al. [20] reported that there is no ideal CMI value.

5. Conclusions

An appropriate crop rotation, promoting a steady long-term contribution of organic matter and increasing the content of organic carbon in the soil, has a positive effect on soil properties, crop productivity, and agroecosystem sustainability. The main results of the long-term experiment after 52 years are as follows:

- The greatest potential for organic carbon sequestration is (a) Norfolk-type crop rotation, where crops that reduce soil fertility are replaced by crops that increase soil fertility every year; (b) intensive crop rotation saturated with intermediate crops. In terms of carbon sequestration, it is most effective to keep perennial grasses for one year while the soil is still full of undecomposed cereal straw from the previous crop.
- Field rotations, with abundant perennial grasses and cereals occupying no more than half of the crop structure, contribute less to carbon sequestration (low CSR), but have greater benefits in the short term as a source of plant nutrients (high CMI).
- In terms of carbon sequestration potential, cereal and three-row crop rotations are impractical, in which cereals are followed by alternating cereals, and there are few or no plants that improve the ratio of carbon to nitrogen in the soil.
- Rye monoculture and green manure crop rotation do not work, where the entire year's crop is plowed for green fertilizer and income from production is lost.
- Black fallow without manure fertilization, compared to crop rotation, reduces the amount of organic carbon in the soil up to two times, the carbon management index by 2–5 times, and poses the greatest danger to the potential of carbon sequestration in agriculture.

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Appendix A

Crop Rotation Sequences

Crop Rotation	Crop Rotation Components
Continuous black fallow (FAL)	Continuous black fallow
Three-course (TC)	(1) black fallow; (2) **winter rye** (*Secale cereale* L.); (3) oat (*Avena sativa* L.).
Cereal (CE)	(1) vetch and oats (*Vicia sativa* L. + *Avena sativa* L.) mixture for green forage; (2) **winter wheat** (*Triticum aestivum* L.); (3) oats (*Avena sativa* L.); (4) **spring barley** (*Hordeum vulgare* L.).
Fodder (FOD)	(1) **spring barley** (*Hordeum vulgare* L.). + undersow; (2) perennial grasses grasses (*Trifolium pratense* L. + *Phleum pratense* L.) (first year); (3) perennial grasses grasses (*Trifolium pratense* L. + *Phleum pratense* L.) (second year); (4) perennial grasses grasses (*Trifolium pratense* L. + *Phleum pratense* L.) (third year); (5) perennial grasses grasses (*Trifolium pratense* L. + *Phleum pratense* L.) (fourth year); (6) flax (*Linum usitatissimum* L.); (7) corn (*Zea mays* L.); (8) fodder beet (*Beta vulgaris* L.).
Winter rye monoculture (MONO)	(1) **winter rye** (*Secale cereale* L.).
Norfolk (NOR)	(1) clover–timothy mixture (*Trifolium pratense* L. + *Phleum pratense* L.) (2) **winter wheat** (*Triticum aestivum* L.); (3) potatoes (*Solanum tuberosum* L.); (4) **spring barley** (*Hordeum vulgare* L.).
Field rotation with row crops (FWR)	(1) **winter wheat** (*Triticum aestivum* L.) + **undersow**; (2) perennial grasses (*Trifolium pratense* L. + *Phleum pratense* L.) (first year); (3) perennial grasses (*Trifolium pratense* L. + *Phleum pratense* L.) (second year); (4) **winter rye** (*Secale cereale* L.); (5) sugar beet (*Beta vulgaris* L.); (6) **spring barley** (*Hordeum vulgare* L.); (7) oat (*Avena sativa* L.); (8) black fallow.
For green manure (FGM)	(1) lupines (*Lupinus angustifolius* L.) for green manure; (2) winter rye (*Secale cereale* L.); (3) winter rape (*Brassica napus* L.) for green manure; (4) **winter rye** (*Secale cereale* L.); (5) potatoes (*Solanum tuberosum* L.); (6) **spring barley** (*Hordeum vulgare* L.).

Crop Rotation	Crop Rotation Components
Intensive (INT)	(1) vetch–oat (*Vicia sativa* L. + *Avena sativa* L.) mixture for fodder + undersow; (2) perennial grasses (*Trifolium pratense* L. + *Phleum pratense* L.) (first year); (3) **winter rye** (*Secale cereale* L.) and, after an intermediate crop, winter rape (*Brassica napus* L.); (4) potatoes (*Solanum tuberosum* L.) and, after an intermediate crop, winter rye (*Secale cereale* L.) for fodder; (5) corn (*Zea mays* L.); (6) **spring** barley (*Hordeum vulgare* L.) and, after an intermediate crop, oil radishes (*Raphanus sativus* L.).

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