

Article

The Effects of Crops Together with Winter Cover Crops on the Content of Soil Water-Stable Aggregates in Organic Farming

Mihkel Are ^{1,*}, Tanel Kaart ², Are Selge ³ and Endla Reintam ¹
¹ Chair of Soil Science, Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, 51006 Tartu, Estonia; endla.reintam@emu.ee

² Chair of Animal Breeding and Biotechnology, Institute of Veterinary Medicine and Animal Sciences, Estonian University of Life Science, 51006 Tartu, Estonia; tanel.kaart@emu.ee

³ Chair of Crop Science and Plant Biology, Institute of Agricultural and Environmental Sciences, Estonian University of Life Sciences, 51006 Tartu, Estonia; are.selge@emu.ee

* Correspondence: mihkelare@gmail.com

Abstract: The stability of the soil aggregates is an important soil quality indicator, as it affects the soil's overall functionality. As the soil aggregates are highly affected by agricultural practices, it is essential to know how crops interact with the aggregation process. Therefore, for obtaining more knowledge, this research was conducted in Estonia in an organic crop rotation field experiment from 2012/2013 through 2015/2016 to study the effects of crops (potato → spring barley undersown with red clover → red clover → winter wheat → pea) under different treatments (T_C —control; T_W —winter cover crops; T_{W+M} — T_W with farmyard manure 40 Mg ha^{−1} per crop rotation). The results showed that in the topsoil (5–10 cm), the soil water-stable aggregate (WSA) content (determined by the wet sieving method) from highest to lowest was following: pea (61.7%), winter wheat (61.6%), spring barley (61.5%), red clover (59.3%), potato (57.1%); whereas in the subsoil (30–35 cm): potato (50.6%), pea (48.5%), red clover (47.9%), spring barley (47.7%), winter wheat (46.4%). Therefore, potato was a noticeable crop, as among the crops, it had the lowest WSA content in the topsoil, while highest in the subsoil. The results shown gave an assumption that the after-effects of some crops (foremost with pea) were noticeable in the soil properties during the following crop. In the topsoil, the differences between crops were significant among crops just for T_W and T_{W+M} treatments. In T_W , potato was lower than spring barley and winter wheat, but not significantly lower than pea or red clover. In the subsoil, significant differences between crops were observed for T_C and T_W treatments: in T_C , potato was just significantly greater than red clover (but similar to other crops), and in T_W , significantly greater than winter wheat. Furthermore, in the topsoil the soil organic carbon (SOC) content was not significantly affected by crops, and the use of winter cover crops generally increased the SOC content while concurrently decreased the WSA content and the soil maximum water holding capacity. This was probably caused by the additional tillage operations which cancelled out the possible benefits for the soil aggregates. As a consequence of the constantly declining SOC content, caused by the weakened soil aggregates, the plant-available P and K contents, especially in the absence of manure applications, decreased as well, probably due to the combination of fixation and removal of plant biomass. Therefore, it is expected that by continuing this trend, the plant growing conditions decline, which in turn will have a negative effect for the aggregate formation and carbon sequestration, which are essential for plant growth.

Keywords: aggregate stability; farmyard manure; maximum water holding capacity; organic farming; winter cover crops



Citation: Are, M.; Kaart, T.; Selge, A.; Reintam, E. The Effects of Crops Together with Winter Cover Crops on the Content of Soil Water-Stable Aggregates in Organic Farming. *Agriculture* **2021**, *11*, 1035. <https://doi.org/10.3390/agriculture11111035>

Academic Editor: Emanuele Radicetti

Received: 9 July 2021

Accepted: 17 October 2021

Published: 22 October 2021

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1. Introduction

The total land area dedicated to organic farming is annually increasing in almost all European Union's (EU) 27 member states [1]. During the eight-year period from 2012 to 2019, the increase was 45.8%, from 9,457,886 ha to 13,794,106 ha, respectively [1]. In terms

of organic area proportion within the utilized agricultural land, Estonia clearly stands out. Based on the data in 2019, its proportion was the second highest of the EU's 27 member states, 22.3%, of which 19.5% was purely organic and 2.8% was in the transition period. For comparison, based on the data in 2018, the average proportion of the organic area within the utilized agricultural land of the 27 EU countries was 8.0% [1]. This, foremost in Estonia, but also in other EU member states, is most likely caused by multiple factors: (i) the EU policy for subsidizing organic farming, by which conventional agricultural land is converted into organic land [2]; (ii) the increased living standard of consumers, enabling them to afford more expensive agricultural products [3]; (iii) the raised consumer awareness about potentially healthier pesticide-free food [4], and (iv) the increased concerns of environmental aspects [5]. Therefore, if everything remains the same, the organic land area, as well as the popularity of organic products both in Estonia and in other EU member states, is expected to rise even more in the future.

From an agricultural point of view, organic farming is very different from conventional farming due to the absence of mineral fertilizers. Thus, for maintaining soil fertility and quality, in terms of sustaining or improving the soil structure by its content of water-stable aggregates (WSA), fewer resources for soil input are available [6]. The organic agriculture greatly relies on the usage of organic fertilizers, foremost in manure, and by the choice of crops within the crop rotation, as well as on the use of winter cover crops [7]. Having a high content of WSA is important, due to the known fact that they affect the soil's water storage and movement as well as gas exchange; thereby the soil functionality in general from the plant growth perspective [8].

The vast majority of previous research that focused on the soil aggregation processes has been conducted under conventional farming, and in those studies, the focus was mostly placed on the crop rotation and tillage types [9] and, in a limited form, on the effects of winter cover crops on aggregate stability [10,11]. However, the effects of individual crops within the crop rotation on the aggregate stability, especially in such pedo-climatic conditions which occur in Estonia, have been currently insufficiently studied.

Among crops, potato, due to its high tillage requirements, is known to reduce the WSA content [12,13] as a consequence of enhanced mineralization of the soil organic matter [14] as well as by the mechanical disruption of aggregates. The effects of legumes on the WSA content are not unambiguously understood. Since legumes, in general, mostly have a smaller fibrous root system than cereals and grasses [15]. Thus, their contribution to aggregate binding could, therefore, be lower [16]. However, their nitrogen-fixing ability, in the Baltic pedo-climatic conditions, can increase the soil fertility and thus increase the root biomass production in the subsequent crops, which, in turn, can increase the soil's organic matter content and, thereby, the WSA content [17]. Additionally, as legumes are known to stimulate the soil microbial activity, they contribute to the abundance of arbuscular mycorrhizal fungi [18], which has positive effects on the soil aggregate stability [16]. Those assumed effects could be even more profound with the use of perennial forage legumes like white clover (*Trifolium repens* L.) or hybrid alfalfa (*Medicago sativa* subsp. *x varia* Martyn), as the soil is undisturbed for a longer period than it is with an annual crop [17]. Both winter and spring cereals, are highly profitable crops and are thus preferred by farmers in the crop rotation, while their effects from a soil structural perspective are not completely clear. The cereal residue management has a substantial impact and can determine the soil organic carbon (SOC) balance [19] and, thus, indirectly influence the WSA content. The winter cereals are also beneficial because they provide soil coverage during the non-growing period and, thus, they act like winter cover crops by protecting the soil from erosion and rain drop forces [20], which may be highly beneficial to the WSA content. However, those effects are highly variable and depend foremost on the soil surface coverage, which is often insufficient [21].

Based on the shortcomings of previous studies, the objective of the current research was to study the effects of crops on the soil aggregate stability and its closely related soil properties in organic farming conditions. Following hypotheses were formulated: (i) with

the manure incorporation the negative effects of potato cultivation on the soil structure can be alleviated to a large extent; (ii) winter cereals are more beneficial for the soil structure than spring cereals, due to their extended period of soil coverage; (iii) the cultivation of legumes, regardless of whether they are annual or perennial, are more beneficial for the soil structure than cereals. Therefore, to test those proposed hypotheses, this study was conducted on a previously established organic field experiment, located in Estonia, which had a five-year crop rotation (pea, potato, spring barley, red clover, winter wheat).

2. Materials and Methods

2.1. Field Experiment Description

The study was conducted in the period of 2012/2013 through 2015/2016 on an organic farming experimental field located in Estonia near Tartu (N 58°21'54", E 26°39'59"). The soil was a *Stagnic Luvisol* (LV-st-lo) [22] with a sandy loam texture (sand: 56.5%; silt: 34.0%; clay: 9.5%) based on the FAO classification. This type of soil represents ~6% of the total Estonian land area (same as in Europe overall) and ~15% of the Estonian arable land and is mostly located in the southeastern part of Estonia.

Estonia, except the western coast with its islands, is located in a humid continental climate region. The data on air temperature and precipitation were based on the Estonian Environment Agency weather station measurements taken near Tartu in Tõravere (N 58°15'50.27", E 26°27'41.67"), located 16.5 km away from the field experiment (Table 1). According to the weather station data, there was a high seasonal and annual variability in both the temperature and precipitation. The whole study period (2012/2013 to 2015/2016) compared with the long-term data (1987–2016) was 0.5 °C, or 8.2%, higher in temperature and 15 mm, or 2.2%, higher in precipitation than the average. In 2013, both the overall precipitation (541 mm) and the precipitation in two consecutive months in June (35 mm) and July (59 mm), were the lowest during the study period. This, in addition to relatively high mean temperatures in the summer, especially in June (18.2 °C), indicated a drought period in the summer of 2013.

Table 1. The average air temperature and sum of precipitation, during the years of study and compared with long-term (30-year) averages.

Temperature (°C):							
Quarter	2012	2013	2014	2015	2016	2012–2016	1987–2016
Q1	−5.0	−5.8	−1.8	0.3	−3.0	−3.1	−3.1
Q2	10.4	12.4	11.0	10.3	12.1	11.2	10.9
Q3	15.4	15.5	16.3	15.4	15.7	15.7	15.3
Q4	0.7	4.4	1.9	3.7	1.1	2.4	1.4
Average	5.4	6.7	6.9	7.5	6.5	6.6	6.1
Precipitation (mm):							
Quarter	2012	2013	2014	2015	2016	2012–2016	1987–2016
Q1	139	85	85	109	155	115	120
Q2	205	144	240	206	279	215	173
Q3	230	161	224	183	205	200	213
Q4	198	151	153	124	150	155	165
Total	772	541	701	622	789	685	671

Notes: Q1—January, February, March; Q2—April, May, June; Q3—July, August, September; Q4—October, November, December.

The organic field experiment (30 m × 120 m) consisted of three side-by-side located fields (10 m × 120 m), each with a different treatment: (i) T_C —control without winter cover crops (WCC); (ii) T_W —winter cover crops and (iii) T_{W+M} —winter cover crops with the addition of fermented cattle farmyard manure. All those three fields consisted of 20 individual plots, it total 60 plots; each with a size of 10 m × 6 m. Those plots represented one crop within the crop rotation in four replications. The detailed schema of the experiment was depicted in Table 2. The crops in the crop rotation were: (1) pea (*Pisum sativum* L.), followed by (2) potato (*Solanum tuberosum* L.), followed by (3) spring

barley (*Hordeum vulgare* L.) undersown with red clover (*Trifolium pratense* L.), followed by (4) red clover, followed by (5) winter wheat (*Triticum aestivum* L.). The sowing rates were: (i) pea, 100 seeds m^{-2} ; (ii) potato, 5.3 tubers m^{-2} ; (iii) barley with red clover undersown, 375 and 280 seeds m^{-2} , respectively; and (iv) winter wheat, 450 seeds m^{-2} . As for the winter cover crops: winter rye (*Secale cereale* L.) (220 kg ha^{-1}), rapeseed (*Brassica napus* L. ssp. *oleifera* var. *biennis*) (6 kg ha^{-1}) and their mixture (226 kg ha^{-1}) were sown on T_W and T_{W+M} in autumn after the harvest of potato, pea and winter wheat, respectively. The manure in T_{W+M} was manually applied in April for potato (20 Mg ha^{-1}), spring barley (with red clover undersown) (10 Mg ha^{-1}) and winter wheat (10 Mg ha^{-1}). By average, the fermented cattle farmyard manure contained following: C_{tot} 138 g kg^{-1} , N_{tot} 9.7 g kg^{-1} , P_{tot} 4.6 g kg^{-1} , K_{tot} 8.6 g kg^{-1} , Ca 11.7 g kg^{-1} , Mg 3.4 g kg^{-1} and 44.8% dry matter. Thereupon, manure was plowed with the winter cover crops up to 22 cm into the soil one week before the planting of potato and sowing the spring barley together with red clover.

Table 2. The schema of the field experiment, which reflects the cropping sequence in spring of 2015 and 2016.

2016 Spring			
	T_C	T_W	T_{W+M}
IV	20 potato	40 potato + W_W	60 potato + $W_W + M_{20}$
	19 s. barley	39 s. barley	59 s. barley + M_{10}
	18 red clover	38 red clover	58 red clover
	17 w. wheat	37 w. wheat + W_{WR}	57 w. wheat + $W_{WR} + M_{10}$
	16 pea	36 pea + W_R	56 pea + W_R
III	15 potato	35 potato + W_W	55 potato + $W_W + M_{20}$
	14 s. barley	34 s. barley	54 s. barley + M_{10}
	13 red clover	33 red clover	53 red clover
	12 w. wheat	32 w. wheat + W_{WR}	52 w. wheat + $W_{WR} + M_{10}$
	11 pea	31 pea + W_R	51 pea + W_R
II	10 potato	30 potato + W_W	50 potato + $W_W + M_{20}$
	9 s. barley	29 s. barley	49 s. barley + M_{10}
	8 red clover	28 red clover	48 red clover
	7 w. wheat	27 w. wheat + W_{WR}	47 w. wheat + $W_{WR} + M_{10}$
	6 pea	26 pea + W_R	46 pea + W_R
I	5 potato	25 potato + W_W	45 potato + $W_W + M_{20}$
	4 s. barley	24 s. barley	44 s. barley + M_{10}
	3 red clover	23 red clover	43 red clover
	2 w. wheat	22 w. wheat + W_{WR}	42 w. wheat + $W_{WR} + M_{10}$
	1 pea	21 pea + W_R	41 pea + W_R
2015 Spring			
	T_C	T_W	T_{W+M}
IV	20 pea	40 pea + W_R	60 pea + W_R
	19 potato	39 potato + W_W	59 potato + $W_W + M_{20}$
	18 s. barley	38 s. barley	58 s. barley + M_{10}
	17 red clover	37 red clover	57 red clover
	16 w. wheat	36 w. wheat + W_{WR}	56 w. wheat + $W_{WR} + M_{10}$
III	15 pea	35 pea + W_R	55 pea + W_R
	14 potato	34 potato + W_W	54 potato + $W_W + M_{20}$
	13 s. barley	33 s. barley	53 s. barley + M_{10}
	12 red clover	32 red clover	52 red clover
	11 w. wheat	31 w. wheat + W_{WR}	51 w. wheat + $W_{WR} + M_{10}$
II	10 pea	30 pea + W_R	50 pea + W_R
	9 potato	29 potato + W_W	49 potato + $W_W + M_{20}$
	8 s. barley	28 s. barley	48 s. barley + M_{10}
	7 red clover	27 red clover	47 red clover
	6 w. wheat	26 w. wheat + W_{WR}	46 w. wheat + $W_{WR} + M_{10}$
I	5 pea	25 pea + W_R	45 pea + W_R
	4 potato	24 potato + W_W	44 potato + $W_W + M_{20}$
	3 s. barley	23 s. barley	43 s. barley + M_{10}
	2 red clover	22 red clover	42 red clover
	1 w. wheat	21 w. wheat + W_{WR}	41 w. wheat + $W_{WR} + M_{10}$

Notes: T_C —control treatment without winter cover crops; T_W —treatment with winter cover crops; T_{W+M} —treatment with winter cover crops and with additional fermented cattle farmyard manure application. Roman numbers, in left of the table, indicate the replication number. Superscripted numbers indicate the plot numbers. Winter cover crops: W_W —winter rye; W_R —rapeseed W_{WR} —mixture of winter rye and rapeseed. Farmyard manure application rates: M_{10} —10 Mg ha^{-1} ; M_{20} —20 Mg ha^{-1} .

The pea, winter wheat and spring barley together with red clover were sown with a Kongskilde Combiseed N30 seed driller; depending on the year, at the end of April or at the beginning of May and the winter cereal during late August. The potato was planted with a Juko Ekengards 4100 at the beginning of May. The potato plots were additionally plowed at 25 cm and then harrowed up to 4–5 cm depth before planting. During the growth period, the potato rows were regularly furrowed and hilled. Mechanical weed harrowing was used twice to control weeds in cereals, potato and pea; additionally in potato at a later growth stage, weeds were removed manually. A spring-tine harrow with a working width of 3 m was used for harrowing.

The cereals and peas were harvested between early and mid-August, depending on the maturity and weather conditions, by using a Sampo SR2010 harvester. The red clover yields were harvested for the first time during the end of June and for the second time during the end of August, by a Mühling Mu-H/S 140 flail mower; after the second cut the red clover was plowed into the soil up to 29 cm by using a Kverneland ES80 reversible plow. The potatoes, depending on the weather conditions, were harvested during late August or early September, by using a two-row elevator-type harvester. During the entire experiment, all plant residues (except potato tubers and cereal grains) were returned back to the soil.

2.2. Soil Material

The soil samples were collected during April in all years, one or two weeks before applying manure. Sampling cylinders (average capacity: 88.2026 mL; height: 40 mm; internal diameter: 53 mm) were used to collect undisturbed soil material from the topsoil (5–10 cm) and subsoil (30–35 cm); from both depths four samples were taken. Thus, eight samples per plot were collected. Despite the topsoil being tilled almost annually within the entire depth of 0–30 cm, it was expected that the largest amount of root mass was located at a depth of 5–10 cm and therefore this range was the most relevant for determining the effects of crops.

Each soil-filled cylinder was placed inside a semi-transparent plastic cup and hermetically sealed with a lid. After fieldwork, those cylinders were placed into a cold storage facility (4 °C) to reduce the risk of soil organic matter degradation; to be used later to determine the maximum water holding capacity (W_{max}). The soil material for determining the soil water-stable aggregate (WSA) content was collected from the previously mentioned depths at the same time and stored in zipped transparent plastic bags. To conduct the chemical analyses, a soil auger was used to collect material from the topsoil at 0–23 cm depth.

2.3. Physical Measurements

To determine the soil-water stable aggregate stability, loose, air-dried soil material was gently crushed with a mortar and pestle, to reduce the content of large peds, and sifted through a 2 mm sieve, then 4 ± 0.01 g of sieved soil was weighed and added in four replications into the mesh of an Eijkelkamp's Wet Sieving Apparatus (model: 08.13), which had a 0.25 mm opening. The soil samples, within the sieves, were slowly pre-moistened with a fine plant sprayer and then later slowly immersed into the caps filled with purified water. The device and the procedure were described in more details by Kemper and Rosenau [23], with the exception that instead of the original 0.2% NaOH solution, 0.4% was used, to accelerate the dissolving process of the organic matter. The WSA content calculation process was following:

$$C_{H_2O} = M_{H_2O} - C_{AL} \quad (1)$$

$$C_{NaOH} = M_{NaOH} - C_{316L} - 0.4 \text{ g}_{NaOH} \quad (2)$$

$$WSA\% = \frac{C_{NaOH}}{C_{H_2O} + C_{NaOH}} \times 100 \quad (3)$$

where, " C_{H_2O} " is the weight of dried soil which was dissolved in purified water after three minutes of sieving; " C_{AL} " is the weight of the aluminum cap; " M_{H_2O} " is the combined weight of " C_{H_2O} " and " C_{AL} "; " C_{NaOH} " is the weight of dried soil which was dissolved by sieving in the 0.4% NaOH solution; " C_{316L} " is the weight of the stainless steel cap; " M_{NaOH} " is the combined weight of " C_{316L} "; " 0.4 g_{NaOH} " is the weight of the 0.4% NaOH solution; " $WSA\%$ " is the content, in percentages, of the soil-water stable aggregates.

To determine the soil maximum water holding capacity, the soil-filled sampling cylinders were first weighed and then placed in a water bath for 24 h, with the purpose of ensuring complete saturation of the soil pores. Next, those saturated soil-filled sampling cylinders were placed for 10 min on an expanded polystyrene foam (length: 200 mm; width: 80 mm; height: 25 mm) covered with one layer of filter paper, which acted as an absorbent membrane [24]; then weighed, then placed into a drying oven for 24 h at 105.5 °C and thereupon weighed for the final time.

2.4. Chemical Analysis

The total nitrogen (N_{tot}) content was determined with the Kjeldahl method [25]. The ammonium lactate (AL) method [26] was used to measure the contents of plant-available: (i) phosphorous (P_A), (ii) potassium (K_A), (iii) calcium (Ca_A) and (iv) magnesium (Mg_A). The total carbon content was measured by Dumas combustion method using a VarioMax CNS analyzer (ELEMENTAR, Germany). Considering that the average soil pH_{KCl} was 6.0, and therefore carbonates were absent, it was assumed that the soil total carbon content was equivalent to that of the soil organic carbon (SOC) content.

2.5. Data Analysis

The normality of variables was prior checked to ensure that the preconditions have been fulfilled for the analysis of variance. Multi-factorial analysis of variance (ANOVA) was used to determine the statistical significance of the soil's physical properties (WSA content and W_{max}) individually from both depths (topsoil: 0–5 cm; subsoil: 30–35 cm), between the crops, winter cover crop management systems, yearly differences and their interactions. The same analysis was used in all soil's chemical properties (SOC , N_{tot} , P_A , K_A , Mg_A , Ca_A and $C:N$), but only from the topsoil (0–23 cm). As due to soil disturbances caused by plowing those properties were expected to be homogeneous within the entire plow layer. Additionally, in all ANOVA tests the plots were considered as random factors. The Tukey's HSD (honest significant difference) was used as a *post-hoc* test. The correlations between the WSA content and other physical-chemical properties were calculated in a pair-wise configuration. The data analyses were performed by using Dell *Statistica* version 13.2 (2016); in all tests, results were considered significant if $p < 0.05$.

3. Results

3.1. The Effects of Crops, Treatments, Yearly Differences and Depths on the Soil Water-Stable Aggregate Content

The results of the ANOVA showed that in both depths the interactions between the crops and all factors, for the WSA content, as well as W_{max} , were statistically significant (Table 3). Furthermore, the interactions between crops and treatments, as well as crops and the yearly differences, for the WSA content and W_{max} in were also significant in both depths. The crops were significant for the WSA content and W_{max} in both depths; however, it was remarkable, that in the subsoil the effects of crops for the WSA content and W_{max} , despite being significant, were still considerably weaker ($p = 0.012$ and $p = 0.037$, respectively) than in the topsoil (both $p < 0.001$). The treatments were significant in both depths for the WSA content; however, for the W_{max} , those treatments were significant only in the topsoil. The yearly differences were significant for the WSA content and W_{max} in both depths.

Table 3. Results of the full-factorial analysis of variance from the topsoil (5–10 cm) and subsoil (30–35 cm) between the crops, winter cover crop management systems, yearly differences and their combined interactions of which effects were tested on the soil water-stable aggregate (WSA) content and soil maximum water holding capacity (W_{\max}).

	Topsoil (5–10 cm)		Subsoil (30–35 cm)	
	WSA	W_{\max}	WSA	W_{\max}
C	$F_{4,900} = 17.60$ $p < 0.001$	$F_{4,900} = 14.32$ $p < 0.001$	$F_{4,900} = 3.23$ $p = 0.012$	$F_{4,900} = 2.57$ $p = 0.037$
T	$F_{2,900} = 5.23$ $p = 0.006$	$F_{2,900} = 1.89$ $p = 0.152$	$F_{2,900} = 54.22$ $p < 0.001$	$F_{2,900} = 28.77$ $p < 0.001$
Y	$F_{3,900} = 44.98$ $p < 0.001$	$F_{3,900} = 81.34$ $p < 0.001$	$F_{3,900} = 22.32$ $p < 0.001$	$F_{3,900} = 58.16$ $p < 0.001$
C × T	$F_{8,900} = 3.58$ $p < 0.001$	$F_{8,900} = 3.90$ $p < 0.001$	$F_{8,900} = 1.95$ $p = 0.049$	$F_{8,900} = 3.11$ $p = 0.002$
C × Y	$F_{12,900} = 8.77$ $p < 0.001$	$F_{12,900} = 4.35$ $p < 0.001$	$F_{12,900} = 4.63$ $p < 0.001$	$F_{12,900} = 3.53$ $p < 0.001$
T × Y	$F_{6,900} = 52.30$ $p < 0.001$	$F_{6,900} = 8.06$ $p < 0.001$	$F_{6,900} = 24.81$ $p < 0.001$	$F_{6,900} = 23.19$ $p < 0.001$
C × T × Y	$F_{24,900} = 3.66$ $p < 0.001$	$F_{24,900} = 2.48$ $p < 0.001$	$F_{24,900} = 3.33$ $p < 0.001$	$F_{24,900} = 2.06$ $p = 0.002$

Factors: C—crops; T—winter cover crop management systems; Y—yearly differences. Soil Parameters: WSA—the content of soil water-stable aggregates; W_{\max} —soil maximum water holding capacity.

The averaged WSA content in the topsoil was 24.9% higher than in the subsoil; with a few exceptions the WSA content in the topsoil was always higher than in the subsoil (Table 4). When all years and treatments were averaged, in the topsoil among all crops, potato had the lowest (57.1%) WSA content (significantly in T_W and T_{W+M}), while, at the same time in the subsoil, it had the highest (50.5%) WSA content (significantly in T_C and T_W) among crops. Additionally, in the topsoil, the WSA content in potato treatments steadily decreased from T_C to T_{W+M} , which was generally the opposite with other crops. In the subsoil, the WSA content in potato was also highest in T_C (this time significantly); however, the lowest WSA content was found in T_W . This occurred even though both treatments differed significantly from the control. In the subsoil, all crops had the lowest WSA content in T_W , whereas in the topsoil, only pea had the lowest WSA content in T_W . Furthermore, pea was a notable crop in the topsoil; as compared with others, it was relatively unaffected by treatments and, at the same time, had the highest WSA content (61.7%), followed closely by winter wheat (61.6%) and spring barley (61.5%). In the subsoil, pea (48.6%) had the second highest WSA content as well, and the difference between spring barley (47.7%) and winter wheat (46.4%) increased. In general, if treatments from all years and depths were averaged, pea (55.2%) had the highest, while potato (53.8%) and red clover (53.6%) had the lowest WSA content; thus, the differences were not large. With the interactions between the WSA content and yearly differences, the patterns were not clearly recognizable. However, the period of 2014/2015 was noticeable, as in most cases, the WSA content in crops was much lower than in other years; this was especially drastic in T_W . In the topsoil among all crops, except potato, the usage of farmyard manure contributed to an increase of the WSA content; whereas in T_C there was a decline in all most crops except pea. Furthermore, regardless of depths, most significant differences among crops occurred in T_W and T_{W+M} treatments.

Table 4. The average content of soil water-stable aggregates (%) with the standard error (SE) of mean in the topsoil (5–10 cm) and subsoil (30–35 cm) by crops, winter cover crop management systems and years.

Year		Topsoil (5–10 cm)				
		Pea	Potato	s. Barley	Clover	w. Wheat
T_C	2015/2016	60.7 ± 1.1 ^{Ba}	49.2 ± 2.4 ^{Aa}	52.0 ± 1.4 ^{Aa}	49.4 ± 2.7 ^{Aa}	51.7 ± 2.1 ^{Aa}
	2014/2015	58.4 ± 0.9	57.4 ± 1.8 ^b	53.8 ± 1.4 ^a	55.7 ± 1.6 ^{ab}	57.0 ± 0.8 ^{ab}
	2013/2014	64.4 ± 0.9 ^b	64.5 ± 1.9 ^b	66.8 ± 2.6 ^b	62.2 ± 1.5 ^b	67.1 ± 1.2 ^b
	2012/2013	62.0 ± 1.2 ^a	63.3 ± 1.4	63.8 ± 1.3 ^a	62.7 ± 1.1	63.5 ± 1.3 ^b
	Average	61.4 ± 0.6	58.6 ± 1.2	59.1 ± 1.2 ^a	57.5 ± 1.1	59.9 ± 1.0
T_W	2015/2016	69.0 ± 1.9 ^{BCb}	56.7 ± 1.3 ^{Ab}	63.3 ± 1.3 ^{Bb}	64.0 ± 1.9 ^{Bb}	70.8 ± 1.7 ^{Cb}
	2014/2015	60.0 ± 1.6 ^C	46.9 ± 0.8 ^{Aa}	53.8 ± 1.5 ^{Ba}	52.9 ± 1.5 ^{Ba}	54.7 ± 1.1 ^{Ba}
	2013/2014	51.7 ± 4.3 ^{Aa}	61.3 ± 2.2 ^{Bb}	65.5 ± 1.6 ^{Bb}	61.4 ± 1.0 ^{Bb}	63.6 ± 1.2 ^{Bb}
	2012/2013	61.4 ± 1.1 ^{Aa}	63.1 ± 1.6 ^A	69.6 ± 1.3 ^{Bb}	60.1 ± 1.4 ^A	58.6 ± 1.8 ^{Aa}
	Average	60.5 ± 1.5 ^{AB}	57.0 ± 1.1 ^A	63.0 ± 1.0 ^{Bb}	59.6 ± 0.9 ^{AB}	61.9 ± 1.0 ^B
T_{W+M}	2015/2016	72.2 ± 1.5 ^{Bb}	56.8 ± 2.0 ^{Ab}	65.8 ± 1.5 ^{Bb}	68.2 ± 1.9 ^{Bb}	68.6 ± 1.6 ^{Bb}
	2014/2015	60.2 ± 1.5 ^B	49.7 ± 2.5 ^{Aa}	63.8 ± 2.4 ^{Bb}	59.6 ± 2.2 ^{Bb}	61.3 ± 1.8 ^{Bb}
	2013/2014	53.6 ± 1.4 ^a	52.5 ± 1.1 ^a	55.9 ± 1.8 ^a	56.2 ± 1.1 ^a	53.9 ± 1.4 ^a
	2012/2013	67.3 ± 1.6 ^{Bb}	63.4 ± 1.5 ^{AB}	63.5 ± 1.3 ^{ABa}	58.9 ± 1.7 ^A	68.1 ± 1.1 ^{Bb}
	Average	63.3 ± 1.1 ^B	55.6 ± 1.1 ^A	62.3 ± 1.0 ^{Bab}	60.7 ± 1.0 ^B	63.0 ± 1.0 ^B
Year		Subsoil (30–35 cm)				
		Pea	Potato	s. Barley	Clover	w. Wheat
T_C	2015/2016	46.6 ± 1.1	50.3 ± 3.0 ^b	52.0 ± 2.9 ^b	45.7 ± 3.9 ^{ab}	57.4 ± 3.5 ^b
	2014/2015	49.1 ± 2.8 ^{ABb}	57.3 ± 1.8 ^{Bb}	41.9 ± 3.0 ^{ABb}	45.9 ± 4.7 ^{ABb}	43.2 ± 2.2 ^{Ab}
	2013/2014	54.1 ± 2.8	52.6 ± 3.0	55.2 ± 4.1	50.1 ± 3.3 ^{ab}	47.7 ± 3.8 ^{ab}
	2012/2013	59.1 ± 2.1 ^b	63.9 ± 2.7 ^b	54.3 ± 4.3	55.5 ± 3.0	58.1 ± 2.4
	Average	52.2 ± 1.1 ^{ABb}	56.0 ± 1.5 ^{Bb}	50.9 ± 1.9 ^{ABb}	49.3 ± 1.9 ^{Aab}	51.6 ± 1.7 ^{ABb}
T_W	2015/2016	52.9 ± 3.4 ^B	52.2 ± 2.0 ^{Bb}	50.2 ± 1.6 ^{ABb}	56.4 ± 2.1 ^{Bb}	42.5 ± 2.2 ^{Aa}
	2014/2015	29.3 ± 3.4 ^a	36.2 ± 3.1 ^a	31.9 ± 1.8 ^a	28.7 ± 1.5 ^a	27.7 ± 1.9 ^a
	2013/2014	52.4 ± 3.1 ^B	42.9 ± 3.1 ^{AB}	33.3 ± 3.1 ^A	38.8 ± 3.7 ^{Aa}	37.1 ± 3.7 ^{Aa}
	2012/2013	42.5 ± 3.4 ^a	52.0 ± 1.9 ^a	48.8 ± 4.7	51.5 ± 5.1	45.3 ± 5.5
	Average	44.3 ± 2.0 ^{ABa}	45.8 ± 1.6 ^{Ba}	41.0 ± 1.8 ^{ABa}	43.8 ± 2.1 ^{ABa}	38.2 ± 2.0 ^{Aa}
T_{W+M}	2015/2016	45.3 ± 2.3	42.0 ± 2.2 ^a	40.6 ± 1.4 ^a	41.3 ± 3.2 ^a	42.3 ± 2.6 ^a
	2014/2015	61.1 ± 1.4 ^{Bc}	60.2 ± 1.1 ^{Bb}	48.4 ± 3.0 ^{Ab}	53.9 ± 2.3 ^{ABb}	48.8 ± 1.9 ^{Ab}
	2013/2014	51.8 ± 2.8 ^B	36.7 ± 2.5 ^A	54.6 ± 4.2 ^B	54.8 ± 3.3 ^{Bb}	53.7 ± 1.5 ^{Bb}
	2012/2013	39.1 ± 3.3 ^{Aa}	61.2 ± 4.1 ^{Bab}	60.9 ± 2.1 ^B	52.7 ± 2.6 ^B	52.4 ± 2.5 ^B
	Average	49.3 ± 1.6 ^{ab}	50.0 ± 1.9 ^a	51.1 ± 1.7 ^b	50.7 ± 1.6 ^b	49.3 ± 1.2 ^b

Soil water-stable aggregate (WSA) content (%)

Notes: T_C —control treatment without winter cover crops; T_W —treatment with winter cover crops; T_{W+M} —treatment with winter cover crops and with additional fermented cattle farmyard manure application. Means (\pm SE) with different upper case letters (^A, ^B, ^C) within a row are significantly different (Tukey's HSD test; $p < 0.05$) between crops. Means (\pm SE) with different lower case letters (^a, ^b, ^c) within columns are significantly different (Tukey's HSD test; $p < 0.05$) between winter cover crop management treatments.

3.2. The Effects of Crops, Treatments, Yearly Differences and Depths on the Soil Maximum Water Holding Capacity

In the topsoil the lowest W_{\max} values among the crops occurred under spring barley, which, in most treatments, were statistically significant; in the subsoil however, this did not occur (Table 5). The study also revealed that in the topsoil the W_{\max} values with red clover and winter wheat steadily increased from T_C to T_{W+M} . In the subsoil, however, this same pattern occurred only with spring barley. The W_{\max} shared a similar sharp decline in 2014/2015 as with the WSA content, because those soil properties were positively correlated by each other (in the topsoil: $r = +0.25$; $p < 0.001$; $N = 240$ and in the subsoil: $r = +0.57$; $p < 0.001$; $N = 240$). However, during the study period, the W_{\max} , compared to the WSA content, had a much steeper decline, which was even noticeable in the manure applied T_{W+M} treatment.

3.3. The Effects of Crops, Treatments and Yearly Differences on the Soil Organic Carbon Content

Based on the ANOVA results, the crops had no significant effect ($p = 0.380$) on the SOC content, but the treatments and yearly differences had ($p = 0.048$ and $p = 0.004$, respectively) (Table 6). During the study period a declining trend in the SOC content was noted among all crops; if all treatments were averaged, the SOC content declined 7%, from 1.64% to 1.53%; however, the decline was most severe in T_C by 11.4%, from 1.61% to 1.53% and least

severe with T_{W+M} by 4.1%, from 1.67% to 1.60%. Despite the crops having no statistically significant effects on the SOC content, it was still noticed during the study period that the decline of the SOC content was highest under potato by average 15.1%, from 1.68% to 1.46%, and in T_C even 26.2%, from 1.72% to 1.36%. It was also noticeable that the lowest decline occurred under winter wheat.

Table 5. The average soil maximum water holding capacity (weight %) with the standard error (SE) of mean in the topsoil (5–10 cm) and subsoil (30–35 cm) by crops, winter cover crop management system and years.

Year		Topsoil (5–10 cm)				
		Pea	Potato	s. Barley	Clover	w. Wheat
T_C	2015/2016	26.5 ± 0.4 ^{BC}	26.0 ± 0.5 ^{ABC}	24.2 ± 0.5 ^{Aa}	25.3 ± 0.3 ^{ABa}	27.8 ± 0.7 ^C
	2014/2015	30.0 ± 1.1 ^{Bb}	30.2 ± 1.7 ^{Bb}	23.8 ± 0.5 ^A	28.4 ± 0.8 ^B	26.7 ± 0.8 ^{ABab}
	2013/2014	33.4 ± 0.9 ^{Bb}	31.3 ± 0.7 ^{AB}	29.1 ± 1.1 ^A	30.1 ± 0.9 ^{ABa}	28.8 ± 0.7 ^A
	2012/2013	26.2 ± 0.5 ^{Aa}	27.0 ± 0.6 ^{AB}	29.0 ± 0.6 ^B	28.1 ± 0.9 ^{AB}	26.6 ± 0.7 ^{AB}
	Average	29.0 ± 0.5 ^B	28.6 ± 0.6 ^{Bb}	26.5 ± 0.5 ^A	28.0 ± 0.4 ^{ABa}	27.5 ± 0.4 ^{AB}
T_W	2015/2016	28.0 ± 0.5	26.0 ± 1.3	26.8 ± 0.9 ^b	28.2 ± 0.8 ^b	28.3 ± 0.4
	2014/2015	24.5 ± 0.4 ^{Aa}	23.6 ± 0.7 ^{Aa}	23.8 ± 0.7 ^A	28.0 ± 0.9 ^{AB}	25.4 ± 0.8 ^{ABa}
	2013/2014	29.5 ± 1.1 ^a	30.3 ± 0.7	30.4 ± 0.9	32.1 ± 0.5 ^{ab}	31.6 ± 0.9
	2012/2013	29.9 ± 0.8 ^{Bb}	27.6 ± 1.0 ^{AB}	28.8 ± 0.5 ^{AB}	30.2 ± 1.1 ^B	26.4 ± 0.6 ^A
	Average	28.0 ± 0.5 ^{AB}	26.9 ± 0.6 ^{Aa}	27.5 ± 0.5 ^A	29.6 ± 0.5 ^{Bb}	27.9 ± 0.5 ^{AB}
T_{W+M}	2015/2016	27.6 ± 0.9 ^{AB}	26.4 ± 0.5 ^{AB}	25.1 ± 0.7 ^{Aab}	26.4 ± 0.7 ^{ABab}	28.2 ± 0.8 ^B
	2014/2015	25.8 ± 0.6 ^{ABa}	27.5 ± 0.7 ^{BCb}	23.8 ± 0.8 ^A	29.6 ± 0.8 ^C	28.3 ± 0.8 ^{BCb}
	2013/2014	31.2 ± 1.3 ^{ABab}	29.7 ± 0.8 ^A	29.7 ± 0.7 ^A	33.6 ± 0.8 ^{Bb}	29.1 ± 1.0 ^A
	2012/2013	30.0 ± 0.7 ^{ABb}	28.8 ± 0.6 ^{AB}	27.4 ± 0.5 ^A	30.6 ± 1.1 ^B	28.7 ± 0.9 ^{AB}
	Average	28.6 ± 0.5 ^{BC}	28.1 ± 0.4 ^{ABab}	26.5 ± 0.4 ^A	30.0 ± 0.5 ^{Cb}	28.6 ± 0.4 ^{BC}
Year		Subsoil (30–35 cm)				
		Pea	Potato	s. Barley	Clover	w. Wheat
T_C	2015/2016	20.8 ± 1.3	21.8 ± 0.8	21.5 ± 0.8 ^{ab}	19.9 ± 0.7 ^a	21.6 ± 1.0
	2014/2015	19.3 ± 0.4 ^{ABa}	21.7 ± 0.6 ^B	18.8 ± 0.9 ^A	20.9 ± 1.0 ^{ABb}	20.3 ± 0.5 ^{ABb}
	2013/2014	23.0 ± 1.6 ^b	24.2 ± 0.7 ^b	24.1 ± 0.7 ^{ab}	20.9 ± 0.7 ^b	22.0 ± 0.9 ^b
	2012/2013	24.2 ± 0.8 ^{AB}	26.5 ± 1.0 ^{Ba}	22.5 ± 1.1 ^A	23.6 ± 1.0 ^{AB}	22.4 ± 0.4 ^A
	Average	21.8 ± 0.6 ^{ABab}	23.5 ± 0.4 ^{Bb}	21.7 ± 0.5 ^{AB}	21.3 ± 0.5 ^{Aa}	21.6 ± 0.4 ^{Ab}
T_W	2015/2016	20.3 ± 0.5 ^A	21.6 ± 0.7 ^{AB}	23.8 ± 0.8 ^{ABb}	23.8 ± 0.6 ^{ABb}	21.3 ± 0.6 ^{AB}
	2014/2015	17.7 ± 0.4 ^a	19.5 ± 1.2	17.7 ± 0.6	18.1 ± 0.4 ^a	17.0 ± 0.2 ^a
	2013/2014	18.9 ± 0.6 ^{ABa}	17.2 ± 1.0 ^{Aa}	21.4 ± 1.2 ^{Ba}	17.1 ± 0.5 ^{Aa}	17.0 ± 0.5 ^{Aa}
	2012/2013	24.2 ± 1.4	22.7 ± 0.8 ^b	24.0 ± 0.8	23.4 ± 1.1	23.8 ± 1.1
	Average	20.3 ± 0.5 ^a	20.2 ± 0.5 ^a	21.7 ± 0.5	20.6 ± 0.5 ^a	19.8 ± 0.5 ^a
T_{W+M}	2015/2016	19.4 ± 0.5	20.9 ± 0.6	19.5 ± 0.4 ^a	20.5 ± 0.6 ^a	20.7 ± 0.6
	2014/2015	22.9 ± 0.7 ^{BCb}	21.9 ± 0.4 ^{BC}	19.2 ± 0.4 ^A	23.0 ± 0.6 ^{Cb}	20.8 ± 0.5 ^{ABb}
	2013/2014	23.8 ± 0.8 ^b	22.9 ± 1.4 ^b	25.2 ± 0.5 ^b	25.2 ± 0.8 ^c	22.1 ± 0.5 ^b
	2012/2013	22.2 ± 0.7 ^A	23.3 ± 0.7 ^{ABb}	25.8 ± 1.2 ^B	22.9 ± 0.7 ^{AB}	24.5 ± 0.7 ^{AB}
	Average	22.1 ± 0.4 ^b	22.3 ± 0.4 ^b	22.4 ± 0.5	22.9 ± 0.4 ^b	22.0 ± 0.3 ^b

Soil maximum water holding capacity (weight %) (W_{max})

Notes: T_C —control treatment without winter cover crops; T_W —treatment with winter cover crops; T_{W+M} —treatment with winter cover crops and with additional fermented cattle farmyard manure application. Means (± SE) with different upper case letters (^A, ^B, ^C) within a row are significantly different (Tukey's HSD test; $p < 0.05$) between crops. Means (± SE) with different lower case letters (^a, ^b, ^c) within columns are significantly different (Tukey's HSD test; $p < 0.05$) between winter cover crop management treatments.

3.4. The Effects of Crops, Treatments and Yearly Differences on the Plant-Available Phosphorus and Potassium

According to the ANOVA results, there was a significant ($p < 0.001$) interaction between the crops and the yearly variation for the K_A content (Table 6). Furthermore, individually, the crops, treatments and yearly variation too had significant ($p = 0.003$, $p = 0.012$ and $p < 0.001$, respectively) effects for the K_A content. However, the P_A content was significantly ($p < 0.001$) affected only by the yearly differences. During the study period the P_A content steadily decreased among all crops (Table 7). Pea was the only crop that showed significant differences between treatments one out of the years (2015/2016). The K_A content among crops during the study period was the lowest under potato (108.8 mg/kg), which was 9.5% lower than under red clover (119.1 mg/kg), which had the second lowest K_A content. However, the K_A content between spring barley (122.5 mg/kg), pea (123.5 mg/kg) and winter wheat (126.8 mg/kg) was very similar. Regardless of the crops, the K_A content

during the entire study period decreased; still, compared with the P_A content, the decline was less severe and fluctuated more between the years.

Table 6. Results of the full-factorial analysis of variance between the crops, winter cover crop management systems, yearly differences and their combined interactions of which effects were tested on different soil chemical properties.

	SOC	N _{tot}	P _A	K _A	Mg _A	Ca _A
C	F _{4,180} = 1.06 <i>p</i> = 0.380	F _{4,180} = 0.92 <i>p</i> = 0.452	F _{4,180} = 0.219 <i>p</i> = 0.928	F _{4,180} = 4.186 <i>p</i> = 0.003	F _{4,180} = 0.445 <i>p</i> = 0.776	F _{4,180} = 0.23 <i>p</i> = 0.920
T	F _{2,180} = 3.09 <i>p</i> = 0.048	F _{2,180} = 2.80 <i>p</i> = 0.063	F _{2,180} = 0.333 <i>p</i> = 0.717	F _{2,180} = 4.575 <i>p</i> = 0.012	F _{2,180} = 6.633 <i>p</i> = 0.002	F _{2,180} = 3.31 <i>p</i> = 0.039
Y	F _{3,180} = 4.61 <i>p</i> = 0.004	F _{3,180} = 98.72 <i>p</i> < 0.001	F _{3,180} = 17.819 <i>p</i> < 0.001	F _{3,180} = 14.287 <i>p</i> < 0.001	F _{3,180} = 103.859 <i>p</i> < 0.001	F _{3,180} = 12.97 <i>p</i> < 0.001
C × T	F _{8,180} = 0.35 <i>p</i> = 0.943	F _{8,180} = 0.41 <i>p</i> = 0.916	F _{8,180} = 0.280 <i>p</i> = 0.972	F _{8,180} = 0.268 <i>p</i> = 0.975	F _{8,180} = 0.149 <i>p</i> = 0.997	F _{8,180} = 0.21 <i>p</i> = 0.989
C × Y	F _{12,180} = 0.92 <i>p</i> = 0.524	F _{12,180} = 0.94 <i>p</i> = 0.504	F _{12,180} = 0.671 <i>p</i> = 0.778	F _{12,180} = 3.056 <i>p</i> < 0.001	F _{12,180} = 0.572 <i>p</i> = 0.862	F _{12,180} = 0.26 <i>p</i> = 0.994
T × Y	F _{6,180} = 0.48 <i>p</i> = 0.822	F _{6,180} = 1.10 <i>p</i> = 0.363	F _{6,180} = 1.279 <i>p</i> = 0.269	F _{6,180} = 0.780 <i>p</i> = 0.587	F _{6,180} = 0.144 <i>p</i> = 0.990	F _{6,180} = 1.66 <i>p</i> = 0.133
C × T × Y	F _{24,180} = 0.48 <i>p</i> = 0.981	F _{24,180} = 0.60 <i>p</i> = 0.932	F _{24,180} = 0.628 <i>p</i> = 0.910	F _{24,180} = 1.052 <i>p</i> = 0.404	F _{24,180} = 0.606 <i>p</i> = 0.926	F _{24,180} = 0.49 <i>p</i> = 0.978

Factors: C—crops; T—winter cover crop management systems; Y—yearly differences. Soil parameters: SOC—soil organic carbon content; N_{tot}—total nitrogen; P_A—plant-available phosphorous; K_A—plant-available potassium; Mg_A—plant-available magnesium; Ca_A—plant-available calcium. Significant results (*p* < 0.05) are marked in bold.

Table 7. The average plant-available phosphorous (P_A) and potassium (K_A) content (mg/kg) and their standard error (SE) of mean within the topsoil by crops, winter cover crop management systems and years.

Year		P _A (mg/kg)				
		Pea	Potato	s. Barley	Clover	w. Wheat
T _C	2015/2016	89.3 ± 4.8 ^a	89.9 ± 7.6	88.8 ± 5.4	98.8 ± 10.3	99.3 ± 10.4
	2014/2015	94.9 ± 16.2	104.7 ± 16.6	109.9 ± 16.2	105.5 ± 12.7	109.0 ± 17.0
	2013/2014	117.2 ± 12.2	112.0 ± 16.5	107.9 ± 9.1	104.6 ± 9.7	116.9 ± 14.8
	2012/2013	143.8 ± 10.9	141.5 ± 8.6	131.2 ± 10.1	134.1 ± 10.2	143.3 ± 12.3
	Average	111.3 ± 7.6	112.0 ± 7.6	109.5 ± 6.2	110.7 ± 6.0	117.1 ± 7.5
T _W	2015/2016	109.9 ± 13.7 ^{ab}	90.7 ± 10.1	92.7 ± 12.1	99.5 ± 17.2	96.5 ± 8.4
	2014/2015	102.8 ± 13.0	112.6 ± 15.0	102.4 ± 13.3	106.4 ± 9.9	112.4 ± 11.5
	2013/2014	106.0 ± 12.5	124.3 ± 13.6	120.5 ± 12.3	118.7 ± 12.5	109.0 ± 12.4
	2012/2013	126.6 ± 16.3	130.4 ± 14.9	137.4 ± 16.8	121.5 ± 18.3	126.0 ± 19.3
	Average	111.3 ± 6.7	114.5 ± 7.2	113.3 ± 7.6	111.5 ± 7.0	111.0 ± 6.6
T _{W+M}	2015/2016	126.1 ± 5.4 ^b	102.2 ± 3.9	105.1 ± 5.5	103.5 ± 8.3	103.7 ± 7.2
	2014/2015	107.7 ± 12.4	107.6 ± 14.7	96.7 ± 10.6	103.4 ± 10.1	129.6 ± 12.9
	2013/2014	118.6 ± 12.7	109.4 ± 8.9	103.4 ± 5.5	137.0 ± 11.7	120.2 ± 10.8
	2012/2014	111.6 ± 9.8	113.7 ± 7.1	151.3 ± 12.0	123.2 ± 11.7	124.9 ± 13.3
	Average	116.0 ± 5.0	108.2 ± 4.4	114.1 ± 6.9	116.8 ± 6.0	119.6 ± 5.7
Year		K _A (mg/kg)				
		Pea	Potato	s. Barley	Clover	w. Wheat
T _C	2015/2016	111.7 ± 6.4	94.0 ± 8.1	93.1 ± 6.2	121.2 ± 16.2	122.5 ± 9.9
	2014/2015	102.9 ± 7.4	97.7 ± 8.9	114.0 ± 14.3	120.8 ± 4.1	126.0 ± 16.0
	2013/2014	112.9 ± 9.1	102.3 ± 15.6	117.0 ± 10.6	109.2 ± 9.7	113.2 ± 8.7
	2012/2013	143.3 ± 16.9	133.3 ± 10.9	135.8 ± 6.1	125.6 ± 4.2	136.2 ± 2.4
	Average	117.7 ± 6.2	106.8 ± 6.4	115.0 ± 5.9	119.2 ± 4.7	124.5 ± 5.1
T _W	2015/2016	130.3 ± 11.7	91.8 ± 11.1	92.1 ± 7.9	96.8 ± 9.4	110.8 ± 7.2
	2014/2015	127.3 ± 13.8	111.8 ± 6.8	121.9 ± 10.9	124.5 ± 8.6	138.3 ± 15.4
	2013/2014	106.5 ± 9.5	102.7 ± 9.7	109.8 ± 8.1	118.0 ± 16.5	105.5 ± 12.7
	2012/2014	121.6 ± 19.4	117.5 ± 16.6	164.6 ± 34.7	123.5 ± 23.7	129.0 ± 21.8
	Average	121.4 ± 6.7	106.0 ± 5.8	122.1 ± 11.0	115.7 ± 7.6	120.9 ± 7.6
T _{W+M}	2015/2016	140.9 ^B ± 3.2	114.4 ^A ± 5.9	108.9 ^A ± 5.8	102.6 ^A ± 5.7	118.3 ^{AB} ± 7.4
	2014/2015	127.4 ^{AB} ± 8.3	113.2 ^A ± 7.4	104.4 ^A ± 7.3	117.5 ^{AB} ± 8.2	153.4 ^B ± 12.1
	2013/2014	131.9 ± 9.9	105.8 ± 4.2	116.3 ± 7.9	138.3 ± 14.7	128.0 ± 9.3
	2012/2013	125.2 ^A ± 5.2	121.3 ^A ± 5.1	192.2 ^B ± 7.7	131.6 ^A ± 5.4	139.9 ^A ± 9.3
	Average	131.3^B ± 3.6	113.7^A ± 2.9	130.5^B ± 9.8	122.5^{AB} ± 5.5	134.9^B ± 5.5

Notes: T_C—control treatment without winter cover crops; T_W—treatment with winter cover crops; T_{W+M}—treatment with winter cover crops and with additional fermented cattle farmyard manure application. Means (± SE) with different upper case letters (^A, ^B, ^C) within a row are significantly different (Tukey's HSD test; *p* < 0.05) between crops. Means (± SE) with different lower case letters (^a, ^b, ^c) within columns are significantly different (Tukey's HSD test; *p* < 0.05) between winter cover crop management treatments.

4. Discussion

The reason why the topsoil potato had the lowest WSA content among all crops was most likely caused by the high number of tillage operations [27], which were further intensified by the use of WCC [11]. However, the reasons why in the subsoil potato had the highest WSA content, especially in the control treatment, were not completely clear. The first possible explanation could be the lasting after-effects of pea in the subsoil, as at the same soil layer pea had the second highest WSA content. The other possible explanation could be the relocation of dissolved organic matter from the topsoil into the subsoil [28], which could contribute to improvements in the soil structure. The reason why the WSA content among crops, except in potato, was higher in the topsoil than in the subsoil can be primarily associated with the decline of the SOC content by depth [17], as in the present study a positive correlation ($r = +0.27$; $p < 0.001$; $N = 240$) between the SOC content and the WSA content occurred (Table 8).

Table 8. Pearson's correlations between aggregate stability soil chemical properties.

	WSA	SOC	N _{tot}	P _A	K _A	Mg _A	Ca _A
WSA	n/a	n/a	n/a	n/a	n/a	n/a	n/a
SOC	+0.27 ***	n/a	n/a	n/a	n/a	n/a	n/a
N _{tot}	+0.02	+0.48 ***	n/a	n/a	n/a	n/a	n/a
P _A	+0.24 ***	+0.54 ***	+0.34 ***	n/a	n/a	n/a	n/a
K _A	+0.19 **	+0.44 ***	+0.40 ***	+0.77 ***	n/a	n/a	n/a
Mg _A	+0.03	+0.23 ***	+0.54 ***	+0.61 ***	+0.61 ***	n/a	n/a
Ca _A	−0.03	+0.32 ***	+0.37 ***	+0.67 ***	+0.54 ***	+0.61 ***	n/a

Notes: WSA—the content of soil water-stable aggregates; SOC—soil organic carbon content; N_{tot}—total nitrogen; P_A—plant-available phosphorous; K_A—plant-available potassium; Mg_A—plant-available magnesium; Ca_A—plant-available calcium; n/a—not applicable. Number of data points: 240. Significant results are marked with: **— $p < 0.01$; ***— $p < 0.001$.

Furthermore, as the subsoil was located below the plow layer, it was unaffected by direct soil disturbances caused by the tillage, which further increased the contrasts between those soil layers. The high variability of the WSA content over the years was nothing novel, especially on such sandy-textured soils [13,29]. In the current study, those annual variations, besides the coarse soil texture, were most likely caused by the combination of the wetting-drying and freezing-thawing cycles [30], as well as by differences in plant growth, especially in the root development [31], and in the tillage [32]. The reason why, in all crops in the subsoil, the lowest WSA content occurred with the WCC treatments could be due to the disruption of the soil structure during the WCC growth process, either by the additional tillage or by compaction. Still, these consequences were considerably mitigated by the manure application, as the addition of organic matter most likely resulted in an increase in the SOC content. On the other hand, the use of WCC could be directly beneficial for the WSA content, as according to Shepherd et al. [33], the soil surface coverage, by at least 70%, greatly reduces the aggregate disrupting rain drop energy; as well as indirectly as a consequence by the increased SOC content [34]. However, the results of the present study suggest that despite the positive effects of the WCC on increasing the SOC content, the additionally required soil tillage operations cancelled out the possible benefits for the WSA content; such findings were similar to those of Sánchez de Cima et al. [11]. The most rational explanation why, in the topsoil under red clover and winter wheat, the WSA content and W_{max} still increased from the control to the manure-applied WCC treatment despite the lack of dedicated WCC (as those crops already provided soil coverage during the winter) could be due to the after-effects of the previous crop(s), by which, especially by the manure application, the SOC content was increased. It was not fully understood why the crops in 2014/2015, especially with the WCC treatment, had the lowest WSA content and W_{max} . Based on the obtained data, it could be suggested that this was most likely associated with compaction during the WCC sowing process, which were carried out in all years in August, and particularly since August of 2014 had the highest

precipitation with 126 mm, which compared to the study period average of 89 mm, was 42% higher, the increased soil moisture content most likely made the soil more susceptible to compaction [35]. Nevertheless, the late harvesting, mostly caused by late rainfalls, could be an obstructive factor in the future for the growth of WCC as well as for the winter cereals, as with elevated soil moisture content, the soil structure is more susceptible to compaction during the sowing process [36]. Still, as mentioned already earlier, the present soil had precondition which favored large yearly fluctuations in the WSA content.

The limited effects of crops on the SOC content, could be the consequences of the crop rotation, by which the effects of individual crops were evened out. Thus, it could be suggested that more than one growth season is needed to see significant differences between the individual crops and the SOC content. The reason why the SOC content mostly declined during the study period was presumably due to the tillage operations, which, especially under potato, enhanced the mineralization of soil organic matter by disrupting the soil macro-aggregates. The decline could be also caused by insufficient carbon sequestration in the form of organic material input [37]. Although, the WCC treatments, especially with manure application, remarkably helped to lessen the decline, because manure not only enhances the soil directly with SOC, but also enhances the plant biomass production by fertilization [38].

The significant positive correlation ($r = +0.61$; $p < 0.001$; $N = 480$) between the WSA content and W_{\max} clearly indicated the importance of a stable soil structure on its water retention capacity. Even though, in Estonia, the annual precipitation exceeds the evaporation rate, drought periods with various lengths during the growing season still occasionally occur. Therefore, maintaining a high WSA content can help to reduce the volatility of plant yields caused by water deficit during the growing season [39], and it could also help to reduce the leaching of soil nutrients during the wet periods as well. The reason why in the topsoil that the significant lowest W_{\max} occurred in spring barley was most likely due to the after-effects of previously grown potato; therefore, it can be concluded that the destructive effects of potato tillage on the soil water retention lasted longer than on the WSA content. Compared to the WSA content, the greater decline of the W_{\max} during the study period could be an indication that the W_{\max} was more sensitive to the SOC decrease than the WSA content. Limited support for this assumption was found in the correlations where the W_{\max} and the SOC content ($r = +0.33$; $p < 0.001$; $N = 240$) were slightly more correlated than the WSA content and the SOC content ($r = +0.27$; $p < 0.001$; $N = 240$).

The positive correlations of the P_A and K_A content between the WSA and SOC content (Table 8) can be explained in multiple ways. At first, as both those soil nutrient are essential for plant growth, they helped to increase the biomass production and enhanced the root system [17], by which a greater degree of root exudes were released, which acted as transient and temporary binding agents for the aggregates [16]. The second reason can be explained by the complex dynamics and interactions between the soil nutrients, SOC and WSA content [40,41]. For instance, a large amount of the P_A is stored in the inter-aggregated soil organic matter [41,42]. Thus, a disruption of those aggregates will cause mineralization in the organic matter and this, in turn, increases the sorption of phosphorous to silt and clay particles, through which, as a consequence, the soil P_A decreased [41]. While the soil clay content was small, the silt content still contributed to 1/3 of the soil's mineral particles and, thus, its impact on phosphorous, as well as on potassium fixation must not be underestimated [42]. As the phosphorous leaching is negligible, the main reason for the decline was the fixation thru sorption, through which the total pool of phosphorous still remained unchanged [43] and as well as by the removal of plant biomass in the form of plant yields. Despite the above-mentioned positive correlation between the contents of K_A and WSA, the effects of potassium on the soil aggregates are still controversial, although lately, the vast majority of researchers still favor that potassium does have positive effects on the aggregation [44]. However, in the present study, the positive correlation could be related to the low clay content (9.5%) of the soil, as potassium has been found to affect the inter-particle bonds in clays by dispersing clay particles [45]. Thus, in the present context,

the benefits of potassium by the increased biomass production and thus in the carbon sequestration [17], as between the K_A and SOC content, a significant correlation occurred ($r = +0.44$; $p < 0.001$; $N = 240$), which likely outweighed the dispersing effects of clay particles. Compared to the other crops, the lowest K_A content, found under potato, was due to the known fact that this crop has a high potassium requirement [46], and therefore, a great amount of K_A was removed from the soil along with the potato tubers [46]. The second-lowest K_A content, which occurred under with red clover, could also be associated with the highest dry mass yields (data not presented) among the crops, by which large quantities of potassium were removed; however, the difference in this case was that the harvested biomass yields were returned and left on the plots to decompose, through which the potassium was slowly released back into the soil. In this case, some of the released potassium will still eventually be leached out of the soil [47]. The fluctuation in the K_A content over the years could be explained by the complex potassium fixing-releasing processes in this feldspar-rich soil parent material. When compared to the P_A content, the less severe decline in the K_A content could be related to the soil enrichment by atmospheric precipitation. According to the data from the Estonian Environment Research Center near Tartu during 2012–2016, the mean soil enrichment by K^+ with precipitation was $\sim 2.6 \text{ kg ha}^{-1} \text{ yr}^{-1} \pm 0.8 \text{ SE}$. While in general, according to the Estonian soil nutrient gradation classification for this soil texture, based on the Mehlich 3 method, the average P_A content was considered as high, and the K_A content was considered as medium, because they ranged between 81–120 mg/kg and 100–200 mg/kg, respectively [48]. However, in a longer time period, the depletion of those plant-available nutrients could be detrimental to the WSA content and impede the overall soil functionality.

As for the potential limitations of this study, which might affected the results and the interpretation of the conclusion(s), following points have to be highlighted: (1) the absence of a comparison study under conventional farming conditions; (2) the lack of different manure application rates for comparison; (3) the soil clay content was low—with a higher clay content the soil aggregation processes might differed; (4) the duration of the study was relatively short.

5. Conclusions

According to the primarily formulated hypothesizes, by the obtained results of this study: (i) the effects of potato were controversial, as in the topsoil (5–10 cm), among crops, it had the lowest WSA content and W_{\max} ; while in the subsoil (30–35 cm) it had both the highest WSA content and W_{\max} . Furthermore, it was disproved that manure had any noticeable positive effects for the soil structure on potato; (ii) it was disproved that winter cereals were more beneficial for the soil structure than spring barley, as both had a similar WSA content and W_{\max} ; (iii) from legumes, it was confirmed that pea, if averaged from both depths, had the highest WSA content, while the effects of red clover for the WSA content were considered average; still, the differences of pea and red clover compared to the other crops were not significant.

In overall, the differences between the crops were not substantially large, and the obtained results gave the assumption that some of the crops had lasting after-effects to the soil structure-related properties in the following crops. The effects of the WCC were controversial; on the one hand, they did slightly increase the SOC content, but on the other hand, due to the additional tillage operations, they had a destructive effect on the WSA content and W_{\max} . However, if farmyard manure was added, the WCC consequences on the WSA content were largely eliminated. Besides the negative nutrient balance, the decline in the P_A and K_A contents was also the consequence of the declining SOC content, which, inside the soil aggregates, acted as storage for the plant-available nutrients. Therefore, by continuing this trend, especially in the absence of manure applications, the decline in plant biomass yields is obvious. This in turn decreases the stability of soil aggregates and the carbon sequestration, as both are significantly interconnected by each other. Still, as the

aggregation process is complex; based on the limitations of this study, more diverse studies for deeper knowledge of those processes in different aspects are needed.

Author Contributions: Conceptualization, M.A., T.K., A.S. and E.R.; methodology, M.A., A.S., E.R. and T.K.; software, E.R.; validation, A.S. and E.R.; formal analysis, M.A.; investigation, M.A. and E.R.; resources, E.R.; data curation, M.A. and T.K.; writing—original draft preparation, M.A.; writing—review and editing, A.S., T.K. and E.R.; visualization, M.A. and T.K.; supervision, E.R., T.K. and A.S.; project administration, M.A. and E.R.; funding acquisition, E.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by the Horizon 2020 project iSQAPER (project number 635750) and by the ERA-NET Core organic project FertCrop (project number 8-2/T15015PKTK).

Acknowledgments: The authors express their great gratitude to the Chair of Crop Science and Plant Biology for maintaining the field experiment as well as everyone else involved in this.

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

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