Transition to conservation agriculture: how tillage intensity and covering affect soil physical parameters

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Abstract. Conservation agriculture (CA) relies on ~~two~~ three key practices to improve agricultural sustainability—crop rotation, reduced tillage and cover crop usage. Despite known soil physical~~s~~ benefits (reduced soil compaction and strength, enhanced soil porosity and permeability), inconsistent reports on short-term CA results have limited its adoption in the European agroecosystems. To elucidate the short-term effects, a three-year field experiment ~~in the low-lying Venetian plain (Northern Italy)~~ was undertaken in the low-lying Venetian plain (Northern Italy). Bulk density (BD), penetration resistance (PR), ~~and~~ soil ~~hydraulic measures~~~~saturated~~ hydraulic saturated conductivity and sorptivity were used to evaluate ~~results~~ soil quality obtained by combining three tillage intensities (conventional tillage (CT), minimum tillage (MT), ~~no~~ no-tillage (NT)) with three winter soil ~~coverages~~ coverings (bare soil (BS), tillage radish cover crop (TR), winter wheat cover crop (WW)). Among the tillage methods~~ and soil layers~~, CT, on average, reduced BD by +4% (from 1.48 to 1.42 g cm^{-3}) and PR by +3.1% (from 1.69 to 1.64 MPa) ~~better~~ ~~more~~ in the 0-30 cm tilled layer.~~. In comparison, oOther treatments yielded higher values (+4% BD and +3.1% PR) in the same layer.~~ Across the soil profile, reduced tillage coupled with WW improved soil physical~~s~~ properties even below the tilled layer, as evidenced by root growth-limiting ~~threshold~~ condition reductions~~declines~~ (-11% in BD values >1.55 g cm^{-3} and -7% in PR values >2.5 MPa). Soil hydraulic measurements confirmed this positive behaviour; NT combined with either BS or WW produced a soil saturated conductivity of 2.12×10^{-4} m s^{-1} (four-fold that of all other treatments). Likewise, sorptivity increased in NT combined with BS *versus* other treatments (3.64×10^{-4} m s^{-1} *vs* an all-treatment average of 7.98×10^{-5} m s^{-1}). Our results suggest that despite ~~some measure declines~~the increase of BD and PR due to reduced tillage, the strategy improved soil functioning, and particularly soil hydraulic conductivity~~enhances soil physical properties, contrasting the soil compaction threats~~. In the short term, ~~cover crop~~ WW cover crop moderately increased physical soil parameters, whereas TR had negligible effects. This study demonstrates that to quantify CA~~, effects require monitoring~~ several soil physical parameters should be monitored.

1 Introduction

Minimal soil disturbance, permanent soil covering, and crop rotation represent the main pillars of Conservation Agriculture (CA) (FAO, 2017). Adoption of CA not only leads to reduced labour and farm costs~~,~~ but also provides several ecosystem services that increase agroecosystem sustainability. Its hallmarks of reduced soil tillage, applied cover crops (CC), and crop

~~rotated~~ rotation ~~crops~~ generally ~~improve the physical parameters of soil and~~ foster nutrient cycling and soil biological activity (Hobbs et al., 2008), improve soil structure along the full soil profile, while protecting soil organic matter (Hobbs, 2007; Thomas et al., 1996). ~~In general, CA has been shown to enhance most soil physical properties, but some contrasting results have been reported and in different pedoclimatic conditions the CA application seem to have positive, negative, or neutral impact on soil hydraulic properties, soil penetration resistance (PR) and soil compaction (Blanco-Canqui and Ruis, 2018).~~

Despite a growing interest in CA from many agroecosystems and especially in the Americas, European adoption of the practice has faltered (Kassam et al., 2019). One reason behind limited CA adoption in Europe is uncertainty about its effects during the transitional period after conversion from conventional to conservation agriculture (Pittelkow et al., 2015; Rusinamhodzi et al., 2011).

~~Among the benefits of CA is its potential to improve soil structure along the full soil profile, while protecting soil organic matter~~ {Formatting Citation}~~. Nonetheless, contrasting results have been reported, especially in the early years after CA adoption.~~ ~~Negative outcomes have often been obtained in no no-tillage (NT) systems that failed to specify whether or not the soil was permanently covered between two main crops (Blanco-Canqui and Ruis, 2018).~~ ~~In general, n~~Negative reports of the short-term effects of CA on physical soil parameters were previously observed in no-tillage (NT) ~~seem limited to~~on bulk density (BD) (Guan et al., 2014), soil strength (Munkholm et al., 2003; Palm et al., 2014), and soil saturated hydraulic conductivity (Buczko et al., 2006).~~, particularly in no-tillage (NT),~~ Nevertheless, ~~even if~~ the management of the fallow period between two main crops (e.g. bare soil or adoption of cover crops) can affect soil evolution (Blanco-Canqui and Ruis, 2018). ~~The use of CC to minimise the side effects of NT or MT represents a valuable short-term solution to facilitate conversion from conventional agriculture to CA. If cash crops are grown during the spring and summer, then autumn-drilled CC must develop rapidly to cover the soil before winter, and devitalisation must occur in the spring before cash crop seeding. Typically, CCs are used to maintain soil coverage. It consists of cultivating plants between two main crops, leaving the entire biomass on the field after the growing season, and eventually burying it before the subsequent crop is planted (Schipanski et al., 2014). The use of CC is a pivotal strategy for enhancing soil physical properties in reduced tillage systems (Blanco-Canqui et al., 2011).~~

~~Despite a growing interest in CA from many agroecosystems and especially in the Americas, European adoption of the practice has faltered (Kassam et al., 2019). One reason behind limited CA adoption in Europe is uncertainty about its effects during the transitional period after conversion from conventional to conservation agriculture (Pittelkow et al., 2015; Rusinamhodzi et al., 2011).~~ ~~Site-specific trials offer not only a chance to expand what is known about the impact of CA on soil physical parameters, but also an opportunity to determine an optimal tillage – CC combination capable of mitigating local soil threats while simultaneously reducing conversion-time side effects. Indeed, under specific conditions, such as high weed pressure or the presence of a hardpan, occasional tillage is recommended (Liu et al., 2016), whereas, in other situations, implementation of minimal tillage (MT) may provide benefits equal to those of NT (Chen et al., 2017; Teodor et al., 2009).~~ ~~Moreover, efficient use of CC requires careful selection of species, seeding date, and management strategy~~

~~(Daryanto et al., 2018). Differing species may positively impact nutrient cycling, soil properties, and/or weed suppression, although such factors must be cost-effective, since they do not contribute directly to profitability (Ranaldo et al., 2019; Schappert et al., 2019).~~

In the low-lying Venetian Plain of Northern Italy, soils contain low organic carbon, high carbonate, and are micro-structured. The principal threats to such soils are organic matter depletion and compaction (Piccoli et al., 2020). Traditionally, farmers have countered compaction with annual deep ploughings that, in the long-term, may contribute to plough pan formation and foster organic matter mineralization. During the last two decades, only about 1000 ha ~~was~~were converted to no-tillage based CA in the Region. Previous studies showed almost no effect on soil porosity and gas exchanges (Piccoli et al., 2017a, 2017b) and on soil organic carbon (SOC) stock but rather a greater stratification in fine-textured soils (Camarotto et al., 2020; Piccoli et al., 2016)~~,~~ while some compaction-related issues were visible in coarser soils (Piccoli et al., 2020, 2021). On the other hand, through model simulation, Camarotto et al. (2018) hypothesized that the benefits of CA might require longer-term for their exploitation due to the soil inertia to management practices.

~~The use of CC to minimise the side effects of NT or MT represents a~~A valuable short-term solution to facilitate conversion from conventional agriculture to CA is the introduction of CCs. If cash crops are grown during the spring and summer, then autumn-drilled, CC must develop rapidly to cover the soil before winter, and devitalisation must occur in the spring before cash crop seeding. Typically, CCs are used to maintain soil coverage. It consists of cultivating plants between two main crops, leaving the entire biomass on the field after the growing season, and eventually burying it before the subsequent crop is planted (Schipanski et al., 2014). The use of CC is a pivotal strategy for enhancing soil physical properties in reduced tillage systems (Blanco-Canqui et al., 2011). Neverteless, an efficient use of CC requires careful selection of species, seeding date, and management strategy (Daryanto et al., 2018). Differing species may positively impact nutrient cycling, soil properties, and/or weed suppression, although such factors must be cost-effective since they do not contribute directly to profitability (Ranaldo et al., 2019; Schappert et al., 2019). ~~Among the benefits of CA is its potential to improve soil structure along the full soil profile, while protecting soil organic matter (Hobbs, 2007; Thomas et al., 1996). Nonetheless, contrasting results have been reported, especially in the early years after CA adoption.~~ ~~In general, negative reports of the short-term effects of CA on physical soil parameters seem limited to bulk density (Guan et al., 2014), soil strength (Munkholm et al., 2003; Palm et al., 2014), and soil saturated hydraulic conductivity (Buczko et al., 2006). The use of CC to minimise the side effects of NT or MT represents a valuable short-term solution to facilitate conversion from conventional agriculture to CA. If cash crops are grown during the spring and summer, then autumn-drilled CC must develop rapidly to cover the soil before winter, and devitalisation must occur in the spring before cash crop seeding.~~

~~A s~~Suitable CC species for northern Italy agroecosystems ~~is~~ are *Poaceae* (e.g., wheat, barley, oat, ray, and triticale), which already ~~is~~ are well adapted and easily managed by farmers. *Poaceae* can control weeds and reduce nutrient losses. Moreover, ~~its~~ their fibrous root apparatus can positively impact soil physical properties, especially in the shallow soil layer (García-González et al., 2018). Alternatively, to mitigate soil compaction and improve the physical quality of the soil, tillage radish (*Raphanus sativus L.*) "TR" has been broadly applied as a CC (Ciaccia et al., 2019; Crotty and Stoate, 2019). TR is a brassicaceous plant, specifically selected to improve the macro-porosity and pore connection of soil. Its 5 cm (D) × 30 cm (L) taproot counters soil compaction while enhancing water infiltration. While it is killed in the winter, it is easily managed in the spring (in a NT system also) (Büchi et al., 2020). As has been demonstrated by the limited use of CC throughout northern Italy, there is a general lack of knowledge on TR adaptability in such agroecosystems~~,~~ and its effectiveness at improving soil properties.

~~The evolution of soil physical traits is frequently done by measuring soil Bulk Density (BD), soil Penetration Resistance (PR) and soil infiltration (Blanco-Canqui and Ruis, 2020). Even though tThese measurements investigate different soil properties, they are strictly related and can inform also the spatial resolution in athe context of soil compaction threat, either BD, PR and soil infiltration could be adopted as indicators of soil strength, soil porosity and water and gas permeability, are evaluating these soil propertiesed from measures usingat different scales. Specifically, PR is evaluated most often using penetrometers having probes of a few centimetres in diameter, BD is determined from undisturbed soil core samples having a slightly larger diameter, and soil infiltration measurements typically rely on infiltrometers of a far larger size (Al-Shammary et al., 2018; Dexter et al., 2007; Morbidelli et al., 2017). These different measurement scales can greatly affect results, particularly in no-till soils, where not only root penetration, but water and gas penetration, can be principally affected by the presence of bio-pores that create preferential pathways for root development even in what seem like highly-compacted soils.~~ The goals of this study ~~are~~ is to evaluate soil physical traits using ~~these~~ different measurements ~~at different spatial resolution measurements~~ during the transition from conventional tillage to CA. ~~The introduction of reduced tillage system was expected to negatively impact on the studied soil physical properties, but the combination of reduced tillage system with tillage radish was expected to alleviate these drawbacks.~~ For this purpose, BD, PR, and soil hydraulic parameters were monitored from 2018 to 2020 in a field ~~surveys conducted on~~ trials ~~created by~~ combining three different tillage systems with three winter soil coverings. Our starting hypothesis~~i~~ is that ~~T~~the introduction of reduced tillage systems ~~wa~~is expected to negatively impact on the studied soil physical properties, but its ~~the~~ combination ~~of reduced tillage system~~ with tillage radish should ~~was expected~~ be a~~lb~~ble to alleviate these drawbacks.

2 Materials and methods

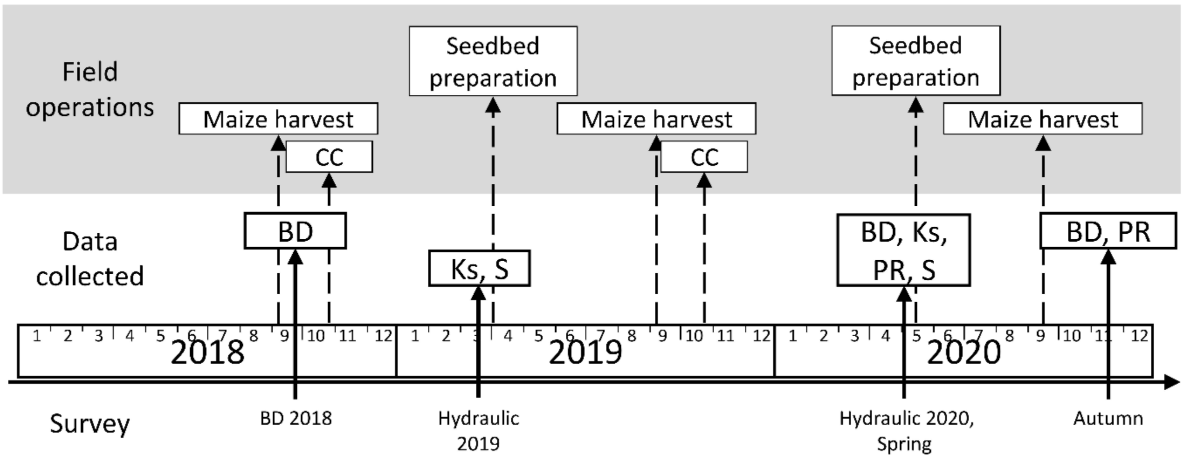
The experiment took place at the Lucio Toniolo Experimental Farm, located in Legnaro, PD (NE Italy, 45° 21 N; 11° 58 E; 6 m a.s.l.), where the climate is sub-humid, with temperatures between -1.5°C on average in January and 27.2°C on average in July. Rainfall~~s~~ reaches 850 mm annually, with ~~a~~ reference evapotranspiration of 945 mm that exceeds rainfall~~s~~ during April to September. ~~Highest~~ The highest rainfall~~s~~ occurs in June (100 mm) and in October (90 mm), while winter is the driest season with an average rainfall~~s~~ of 55 mm. The shallow water table ranges from 0.5 to 2 m in depth, with the lowest values recorded in summer.

The trial, begun in spring 2018, was designed as a ~~split~~ split-plot, with two replicates. A 2-ha area was divided into 18 elementary plots of ~~about~~ 1.111 m^2 each, allocated in two main blocks. Soil at the site is Fluvi-Calcaric Cambisol (FAO-UNESCO, 2008) with a silty loam texture.

At the start of the experiment, the average soil texture of each plot was determined by laser diffraction (Malvern Mastersizer 2000; Malvern Instruments, Malvern, UK) as described in Bittelli *et al.*, 2018. The soil texture was uniform within the experimental unit, with, on average 25% ± 1.19, 57% ± 0.85 and 18% ± 0.36 of sand, silt and clay respectively. Three different tillage treatments were randomized in ~~two blocks~~the man plot, which consisted in cluster of three elementary plots~~plots~~: the conventional tillage (CT) main plot was ploughed to 30 cm and harrowed (15 cm), the minimum tillage (MT) main plot was ~~tilled~~ arrowed to a depth of 15 cm~~ and then harrowed~~, and the ~~no~~ no-tillage (NT) main plot was sod-seeded. Then, three winter soil coverings were randomized in the elementary plots within each of these main plots: TR (*Raphanus sativus L.*), winter wheat (WW – *Triticum aestivum L.*), and bare soil (BS), where no soil cover was present other than the residues from the crop of the previous year. ~~In total, each block consisted inof 9 elementary plots.~~ Cover crops were drilled on the main crop residues in autumn 2018 and 2019. The main crop was always maize (*Zea mays L.*).

2.1 Field surveys

Four parameters were selected to monitor soil physical qualities: ~~bulk density (~~BD~~)~~, ~~penetration resistance (~~PR~~)~~, and saturated hydraulic conductivity (Ks) together with sorptivity (S). The survey timetable is shown in Figure 1.



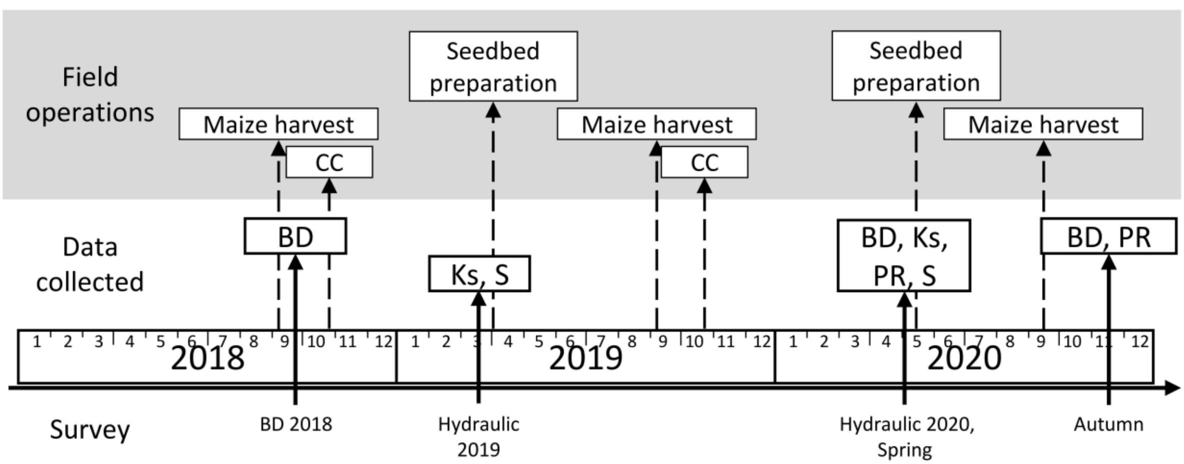


Figure 1. Survey timetable. BD: bulk density, CC: cover crop seeding, Ks: saturated hydraulic conductivity, PR: penetration resistance, S: sorptivity

2.1.1 Bulk density

The surveys were conducted on three sampling dates. Measurements were first performed at the start of the experiment after the first-year harvest (~~BD~~ 2018~~, time 0, September 2018~~). The second collection occurred in 2020 before tillage operations and after CC devitalization (~~May~~Spring 2020). The final sampling was performed in the same year, after the maize harvest but ~~prior to~~before soil preparation and subsequent crop seeding (~~November~~Autuimn 2020) (Figure 1). ~~Hereafter, the first, second, and third BD surveys will be referred to as "2018", "Spring", and "Autumn", respectively.~~A total of 54 undisturbed soil cores (7 cm diameter × 60 cm heigth) were collected during the three years experiment with a hydraulic sampler. Each core was then divided in six layers (7 cm diameter × 10 cm heigth, 385 cm^3 volume), totalling 324 soil samples. ~~Each soil core was considered in 10 cm layers, which yielded six different depth-linked BD values from each sample.~~ All samples were ~~oven~~ oven-dried (~~24~~ 48 hr at 105°C) to calculate BD with the ~~(~~core method~~)~~ (Grossman and Reinsch, 2002) ~~on undisturbed 7 cm diameter soil cores that were collected with a hydraulic probe from the 0-60 cm layer, collectively, a total~~

~~of 54 undisturbed soil cores were collected during the three years experiment, each of which were divided in six 385 cm^3 portion of 10 cm, totalling 324 soil samples, o which BD was determined~~.

2.1.2 Penetration resistance

Penetration ~~Resistance~~ resistance ~~(PR)~~ was measured with a penetrologger (Eijkelkamp, Netherland) throughout the 0-80 cm layer with a 30° 2 cm^2 cone. In each plot, four sampling zones were randomly selected. In each sampling zone, four penetration measurements were performed within an area of 0.25 m^2. Disturbed soil samples were also collected to determine gravimetric water content and soil texture in each 20 cm soil layer (0-20, 20-40, 40-60, and 60-80 cm). The penetrologger ~~measured~~ ranged from 0 to 5 MPa. ~~Noteworthy is the fact that the top value was often reached and eventually exceeded in the 60-80 cm layer, although only the 0-60 cm layer was considered in this study.~~ Two PR samplings were performed ~~in the same fashion~~ in the Spring and Autumn surveys~~ as described above~~, and coincident with the second and third BD measurements (Figure 1). PR values were averaged for each 10 cm of the soil profile and compared with the 2.5 MPa threshold which is considered a critical value above which root growth may be compromised according to Groenevelt et al. (2001).

2.1.3 Saturated hydraulic conductivity and sorptivity

Saturated hydraulic conductivity (Ks) and sorptivity (S) parameters were calculated from the measurements~~d~~ ~~by a~~ of a double-ring infiltrometer on an area of 1300 cm^2, as described in Morbidelli et al. (2017). Philip's equations (Philip, 1969) were fitted to the field data to calculate Ks and S. Two surveys (spring 2019 and spring 2020, March and May respectively) were conducted to measure these parameters after CC termination and before soil preparation, with a single measurement per plot per survey.

2.2 Statistical analyses

A mixed-effects model was applied to test the main effects of tillage, soil covering, and their interactions on all i-th variables for each monitoring period. The sand content, ~~and bulk density~~BD and GWC were tested as covariates. ~~All effects named above~~Tillage, CC, and depth were treated as fixed effects; the ~~plot~~ block effect ~~inside each treatment~~ was treated as random and measurements inside the same plot were considered as nested. All possible first and ~~second~~ second-order interactions between factors were tested, and the model with the smallest AIC (Akaike's Information Criterion) was selected (Schabenberger and Pierce, 2001). Prior to analyses, normality and homoschedasticity were checked through Q-Q plots and residual plots. Post hoc pairwise comparisons of least squares means were performed using the Tukey method to adjust for multiple comparisons at ~~, in case of significant (~~$p<0.05$~~) effects~~.

For ~~penetration resistance~~PR, the percentage of measurements above 2.5 MPa ~~with~~ along the ~~whole~~ soil profile ~~considered~~ was tested with Kruskal-Wallis ANOVA, as these data were the only not-normally distributed. The BD-PR correlation significance was F-tested. All statistical analyses were performed with SAS (SAS Institute Inc. Cary, NC, USA) version 5.1.

3 Results

3.1 Bulk density

The first BD survey ~~was~~ conducted at the beginning of the experiment (~~time 0~~2018) showed ~~. At that time, BD measurements were~~ uniform BD among the experimental plots. In ~~particular~~the tilled layer (0-30 cm), BD ranged between 1.14 and 1.60 g cm^{-3} (average value of 1.40 g cm^{-3})~~ in the tilled layer (0-30 cm)~~. In the deepest layer (30-60 cm), the mean value was higher at 1.49 g cm^{-3} within a range of 1.30 g cm^{-3} and 1.69 g cm^{-3}. No statistical differences were reported among treatements (Figure~~.~~ 2, Table 1).

Table 1. Comparison of p-values among the linear mixed-effect models analysis of bulk density (BD), penetration resistance (PR), saturated hydraulic conductivity (Ks), and sorptivity (S). Effects were considered significant if p≤0.05. GWC: gravimetric water content.

	BD			PR		Ks		S	
	2018	Spring 2020	Autumn 2020	Spring 2020	Autumn 2020	2019	2020	2019	2020
Intercept	0.0329	0.008	0.007	0.095	<0.001	0.207	0.155	0.123	0.118
Tillage	0.8849	<0.001	0.003	<0.001	0.034	<0.001	<0.001	<0.001	<0.001
CC	0.0952	<0.001	<0.001	0.738	0.002	<0.001	0.026	<0.001	<0.001
Tillage*CC	0.6640	<0.001	<0.001	0.006	0.014	<0.001	<0.001	<0.001	<0.001
BD~~ULK~~	#	#	#	0.280	0.369	--	--	--	--
sand	0.4293	<0.001	0.573	<0.001	0.041	0.2002	0.0188	<0.001	<0.001
Depth	0.0000	<0.001	<0.001	<0.001	<0.001	#	#	#	#
Tillage*Depth	0.5307	<0.001	0.001	0.003	<0.001	#	#	#	#
CC*Depth	0.9638	<0.001	<0.001	--	--	#	#	#	#
Tillage*CC*Depth	0.9932	<0.001	<0.001	--	--	#	#	#	#
GWC	#	#	#	0.404	0. 002	#	#	#	#

-- effect not included in the model according to the Akaike Information Criterion; # not applicable.

On the contrary, significant differences were reported in the ~~2020~~ Spring 2020 survey. In the 0-30 cm soil layers, the CT-BS ~~treatment combination~~ displayed the lowest ~~average~~ BD ~~value~~ (1.37 g cm^{-3} or 5.1% lower) among all other treatments. In NT, cover crops TR and WW both seemed to reduce BD values in the 10-40 cm layer (1.54 g cm^{-3} on average) when compared to BS (1.58 g cm^{-3}). Generally, a tillage effect was prevalent in the 10-30 cm soil layer (Figure ~~.~~2) where~~. This was demonstrated by a~~ CT averaged ~~of~~ 1.37 g cm^{-3}, as opposed to the 6.5% higher BD ~~values~~ found in the same layer ~~in~~ of MT and NT. In the ~~deepest~~ deeper layers, BD was generally ~~values were even~~ higher, ranging from 1.54 g cm^{-3} to 1.91 g cm^{-3}. ~~Here, the reduced tillage systems proved to reduce BD moderately, whereas CC produced limited results.~~

The Autumn 2020 BD survey exhibited a greater tillage effect along the soil profile relative to the time-zero survey. The 0-10 cm ~~Bulk density~~BD ~~results in the 0-10 cm layer~~ of NT ~~differed markedly from other treatments. Indeed, they~~ averaged 1.46 g cm^{-3}, 6.6% greater than ~~above (1.46 g cm^{-3})~~ the other treatments~~s~~. In these soil layers~~cases~~, the presence of a cover raised BD values throughout the soil profile by 2.9% (1.41 g cm^{-3}). In the subsequent soil layer (10-20 cm), CT showed the lowest average BD values (1.43 g cm^{-3}), whereas, at depths below 20 cm (20-60 cm), CT treatment resulted in 2.2% higher average BD values (1.57 g cm^{-3}) when compared to the reduced tillage systems (MT and NT). ~~Again, the CC effect seemed limited as TR and WW showed 2.8% higher BD (1.48 g cm^{-3}) values in the 0-30 cm layer.~~In both surveys, CC did not significantly affect BD.

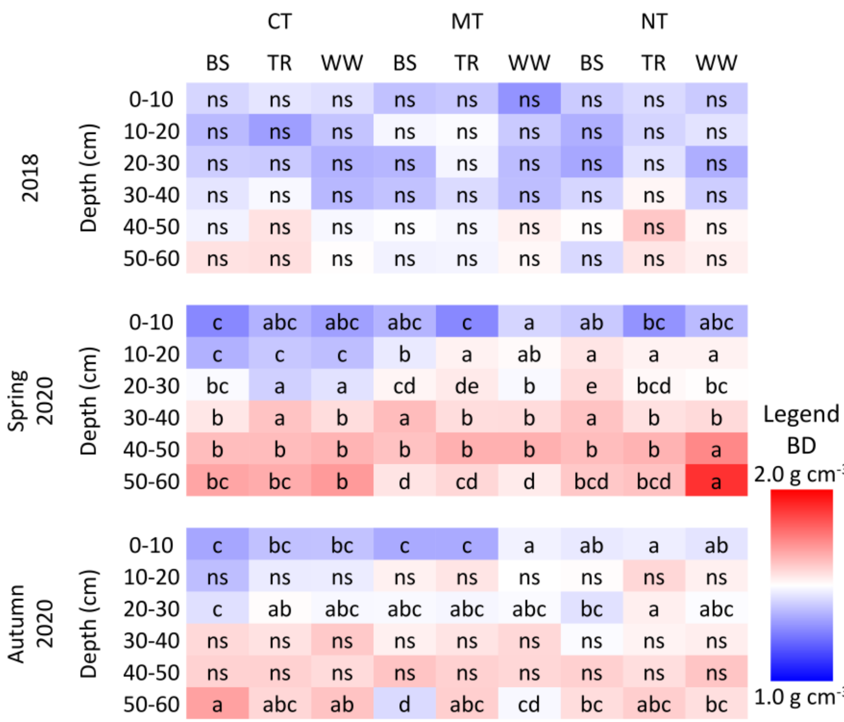
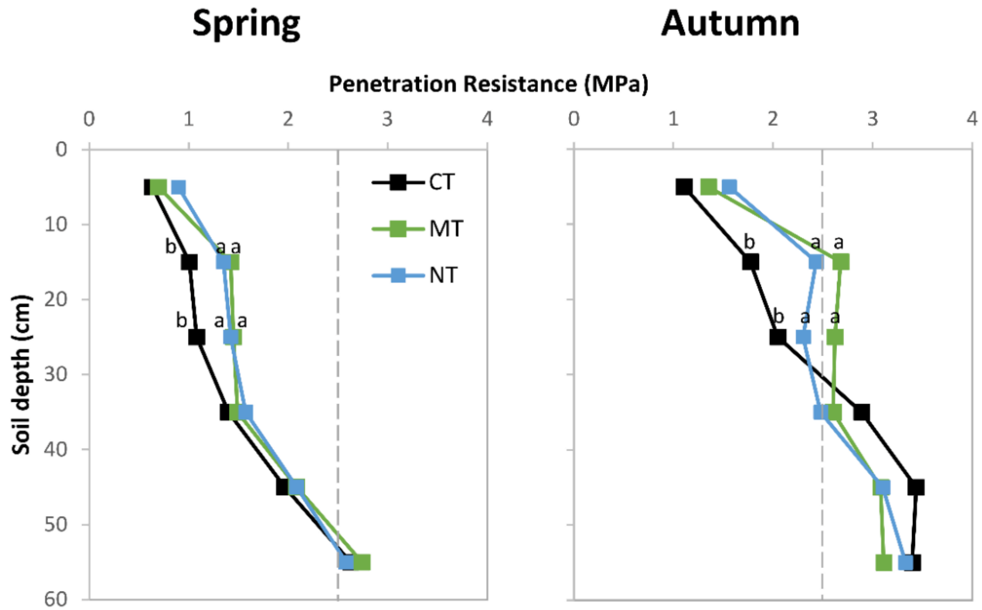


Figure 2. Bulk density (BD) distribution along the 0-60 cm soil profile. For each soil layer, the letters indicate significant effects of tillage x CC according to the Tukey test ($p<0.05$). CT: conventional tillage; MT: minimum tillage; NT: no-tillage; BS: bare soil; TR: tillage radish; WW: winter wheat.

3.3 Penetration resistance

Results indicated that soil structure, soil texture, and soil water content ~~each~~ affected PR in both 2020 surveys (Table 1). Noteworthy is the fact that the ~~top value~~instrumental limit (i.e., 5 MPa) was often reached and eventually exceeded in the 60-80 cm layer, although only the 0-60 cm layer was considered in this study. Soil moisture ~~C~~conditions were, on average, drier during the Autumn 2020 survey (0.163 kg kg^{-1}) than during the Spring 2020 ~~survey~~ one (0.222 kg kg^{-1}), for which average PR values were 2.52 MPa and 1.58 MPa, respectively. During both surveys, ~~the~~ significant differences were observed for tillage × depth and tillage × CC interactions ~~interactions were detected~~ (Table 1). A comparison among the three tillage systems showed that CT exhibited lower PR values than MT and NT in the 10~~to~~-30 cm ~~depth~~ layer in both surveys (Figure~~.~~ 3). Indeed, CT reported ~~an~~ average PR values of 1.04 MPa (Spring 2020) and 1.91 MPa (Autumn 2020), while the reduced tillage treatments increased their PR values by +35.6% (1.41 MPa) and +31.4% (2.51 MPa), respectively.



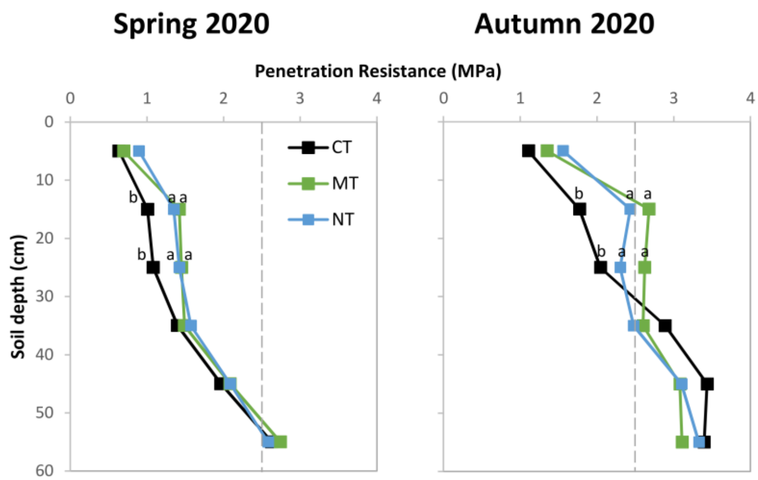


Figure 3. Penetration resistance (PR) along the 0-60 cm soil profile (values averaged every 10 cm). Different letters represent significant differences according to the post-hoc Tukey test (p<0.05). The vertical dashed line indicates the 2.5 MPa threshold according to Groenevelt *et al.* (2001). CT: conventional tillage; MT: minimum tillage; NT: no-tillage.

When the entire 0-60 cm soil profile was considered, CT (regardless of the winter soil covering), as well as MT-TR and NT-BS were associated with the lowest PR values, in the Spring 2020 survey (1.50 MPa, on average, Figure 4). The highest PR value occurred in MT-BS (1.74 MPa). Alternatively, in Autumn 2020, the highest PR was measured in MT-TR (2.81 MPa), while MT-BS, CT-WW, CT-BS, and MT-WW (on average 2.42 MPa) were all among the lowest. CT-TR and the NT treatments resulted in intermediate PR values that ranged between 2.51 MPa (NT-WW) and 2.55 (NT-BS).

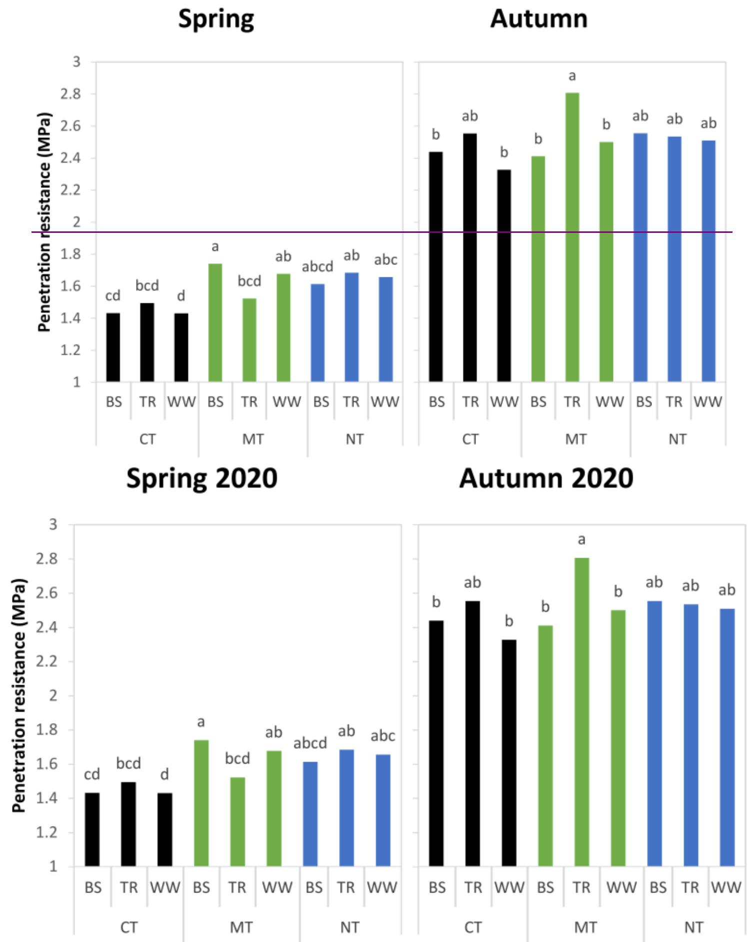
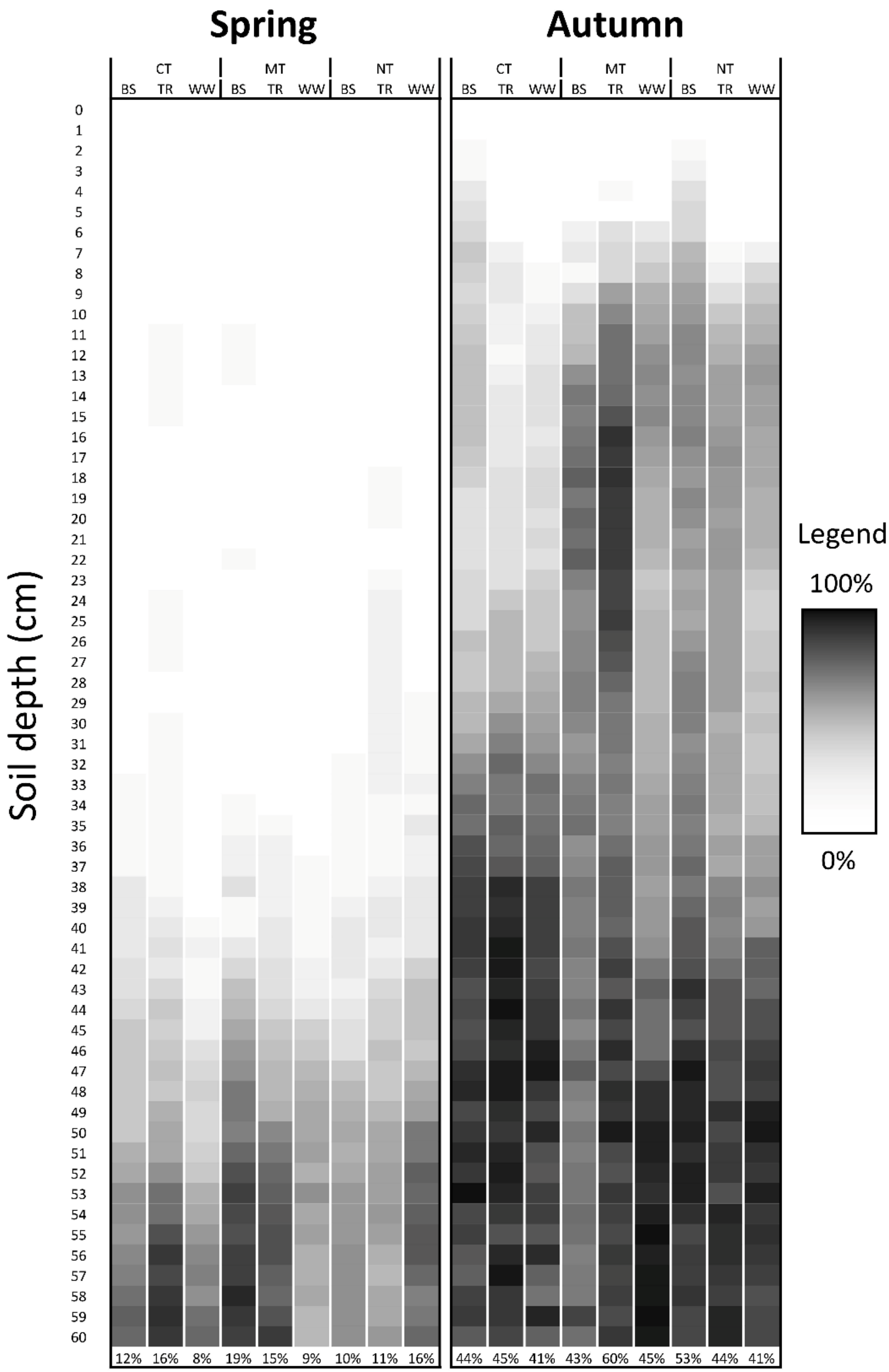


Figure 4. Penetration resistance along the 0-60 cm soil profile. Different letters represent significant differences according to the post-hoc Tukey test with p<0.05. CT: conventional tillage; MT: minimum tillage; NT: no-tillage; BS: bare soil; TR: tillage radish; WW: winter wheat.

The PR values were then compared with the 2.5 MPa limit (Figure~~.~~ 5). During the first survey (Spring 2020) only 13% of measurements were above this threshold, mostly beneath the tilled layer. During the Autumn 2020 survey, the proportion of measures above the threshold rose to 46%, with a high percentage reported throughout the full soil profile. The Kruskal-Wallis one-way ANOVA ~~indicated there was a~~ resulted in a significant ($p<0.05$) effect related to the combination of tillage and CC. ~~Close examination showed that the~~ MT-TR ~~treatment combination~~ resulted ~~with~~ in the highest proportion of over-threshold PR values (60%). It was followed by NT-BS (53%) and all the other treatment ~~combinations~~ ranged between 41% and 45%.



Spring
Autumn
CT
MT
NT
BS
TR
WW
Soil depth (cm)
0
5
10
15
20
25
30
35
40
45
50
55
60
12% 16% 8% 19% 15% 9% 10% 11% 16%
44% 45% 41% 43% 60% 45% 53% 44% 41%
Legend
100%
0%

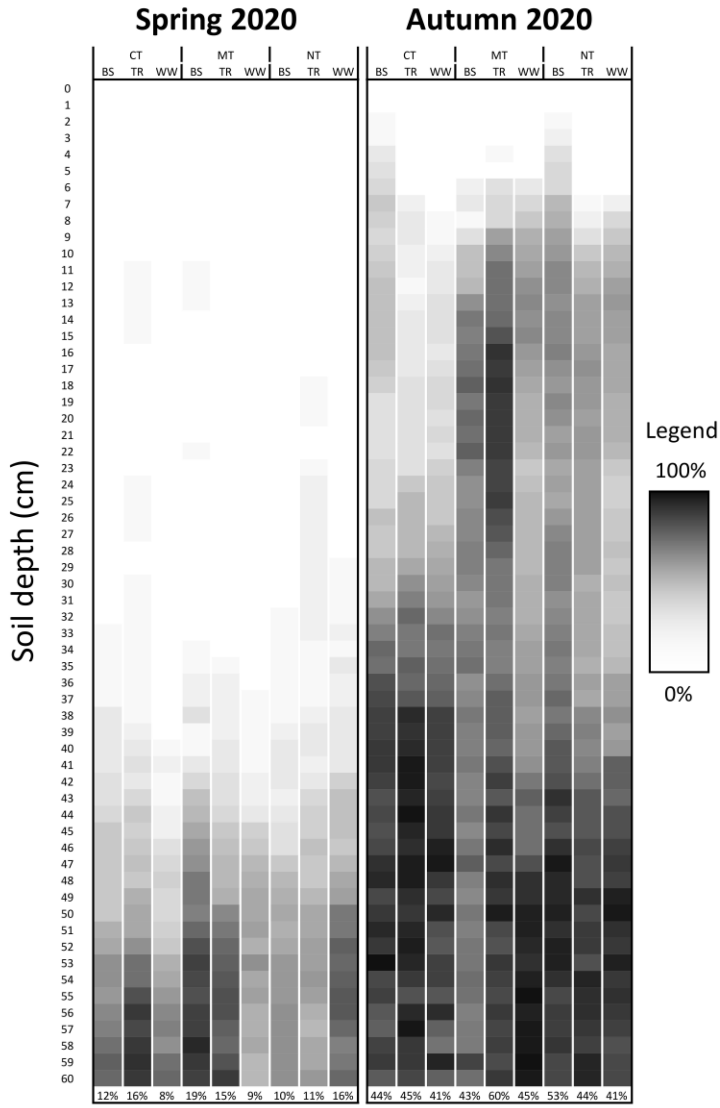


Figure 5. Percentage of penetration resistance measurements above the 2.5 MPa threshold. CT: conventional tillage; MT: minimum tillage; NT: no-tillage; BS: bare soil; TR: tillage radish; WW: winter wheat.

3.4 Soil hydraulic properties

A significant tillage × CC interaction effect was observed on Ks during both the 2019 and 2020 surveys (Figure~~.~~ 6). The ~~combination of~~ NT-WW treatment produced the highest 2019 Ks value, which represented a two-fold increase compared to all other treatments (2.50×10^{-5} m s^{-1} in NT-WW *vs* 1.04×10^{-4} m s^{-1}~~, respectively~~in the other treatments, on average). During the 2020 survey, all treatments exhibited increased Ks values that were 1.6 times higher, on average, than those of 2019. In particular, the combination of either BS or WW with NT~~,~~ had the highest Ks (2.12 $\times10^{-4}$ m s^{-1}), which was more than twice the values of all other treatments (5.14 $\times10^{-5}$ m s^{-1}, on average). It is worth noting that TR displayed no ~~effect in any combination~~interactions with soil tillage in either year.

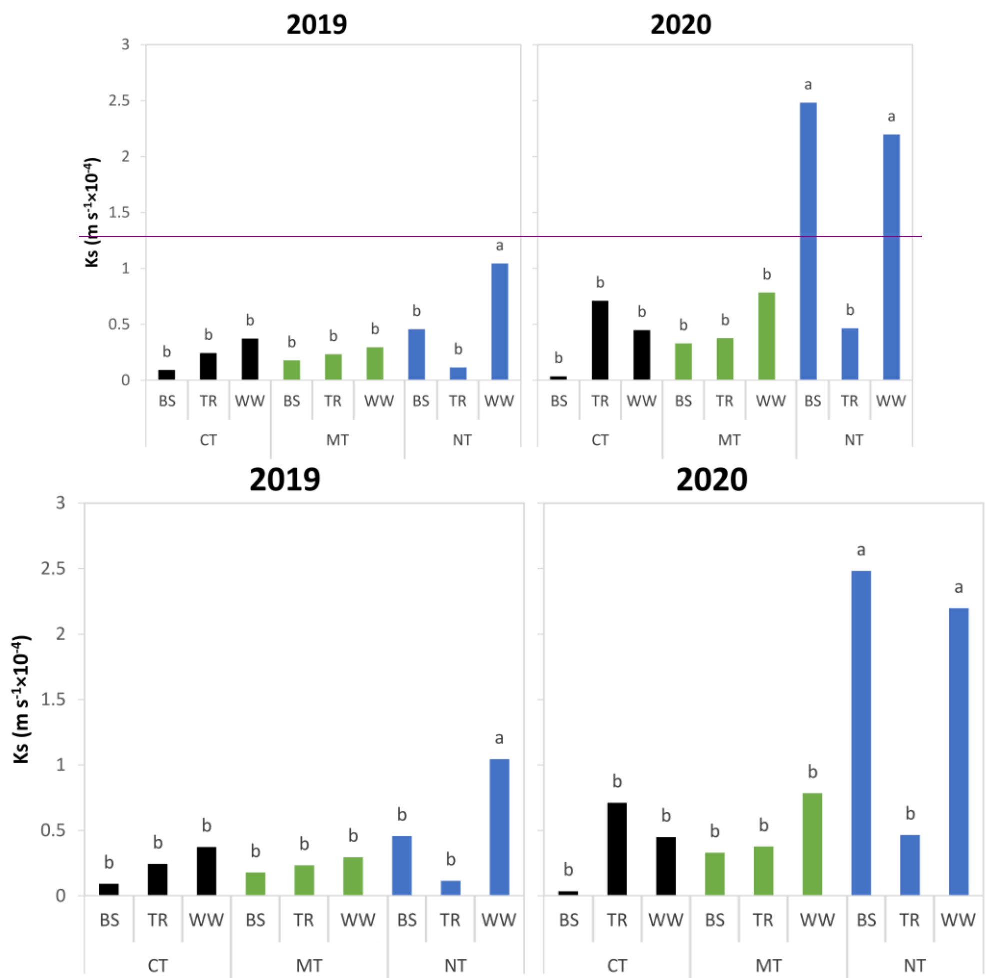


Figure 6. Saturated hydraulic conductivity (Ks) as measured in the two surveys (2019 and 2020). Different letters represent significant differences according to the post-hoc Tukey test ($p<0.05$). CT: conventional tillage; MT: minimum tillage; NT: no-tillage; BS: bare soil; TR: tillage radish; WW: winter wheat.

Sorptivity (S) was affected both by the interaction of tillage × CC and soil texture (Table 1, Fig~~.~~ure 7)~~;~~. The sand content negatively correlated with S. Identical tendencies were observed in both years. Among the ~~various~~ treatments~~-combinations~~, NT-BS reported the highest results, 1.27 $\times10^{-4}$ m s^{-1} in ~~(~~2019~~)~~ and 3.19 $\times10^{-5}$ m s^{-1} in ~~(~~2020~~)~~. Very low values of S were observed in CT-BS (8.5$\times10^{-7}$ m s^{-1}, on average) during the 2020 survey.

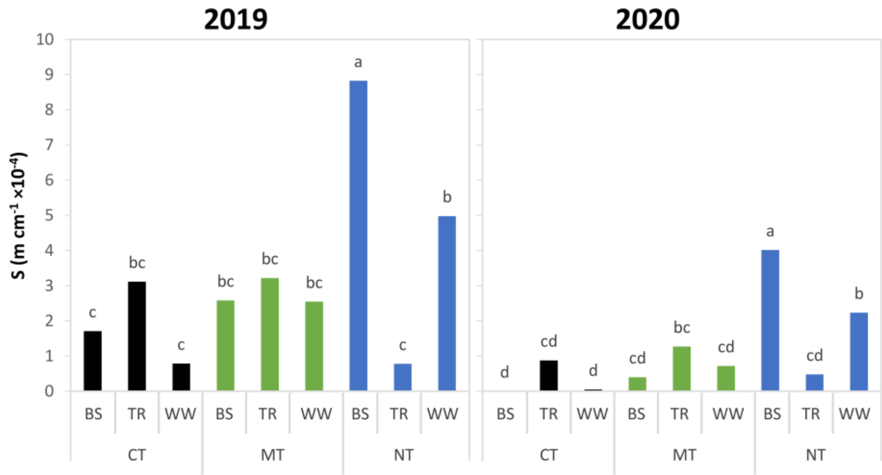


Figure 7. Sorptivity (S) in the two surveys (2019 and 2020). Different letters represent significant differences according to the post-hoc Tukey test (p<0.05). CT: conventional tillage; MT: minimum tillage; NT: no-tillage; BS: bare soil; TR: tillage radish; WW: winter wheat.

3.5 Correlation between bulk density and penetration resistance

A significant ($p<0.01$) positive correlation was found between BD (range of 1.33-1.80 g cm^{-3}) ~~(range of 0.5-2.5 MPa)~~ and PR (range of 0.5-2.5 MPa) ~~(range of 1.33-1.80 g cm^{-3})~~ with 0.36 R^2. At a PR> 2.5 MPa, ~~the~~ no correlation with BD was ~~lost~~detected; and no other regression could be found between the two parameters. At points above the critical limits of PR (2.5 MPa) and BD (1.55 g cm^{-3}), 46% of the observations were detected in CT, 31% in MT, and only 23% in NT, as the red box highlights in Figure~~.~~ 8. Under these limiting conditions, WW reported the fewest (31%), BS intermediated (33%) and TR the highest (36~~5~~%) number of observations~~measurements above this~~ these ~~thresholds~~. ~~Following WW was BS; TR had 35% of observations~~ above the two thresholds~~in the range.~~

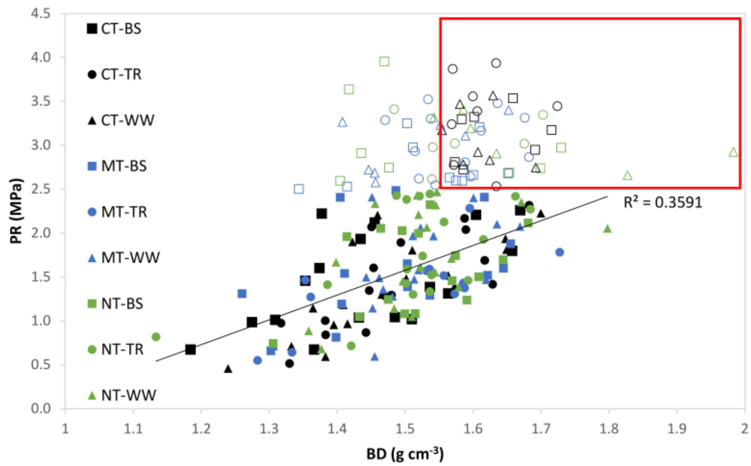


Figure 8. Correlation between bulk density (BD) and penetration resistance (PR). The line represents the significant ($p<0.01$) linear correlation for PR<2.5 MPa and BD <1.8 g cm^{-3}. Closed and open ~~indicators~~ symbols are used for PRs below or above 2.5 MPa, respectively. The red box highlights observations above both 1.55 g cm^{-3} BD and 2.5 MPa PR.

4. Discussion

Collectively, the~~The~~ presented results ~~presented above~~ confirmed that employing a combination of tillage and CC has limited effects in the short term. ~~, as~~ Perego et al. (2019) ~~and Piccoli et al. (2017a)~~ previously reported how the adoption of CA practices is feasible in the Po valley environment. Indeed, after an initial phase required for farmers to develop technical skills, it is possible to reduce the yield gap between conservation and conventional systems and, exploit the beneif related to CA on soil fertility and health (Perego et al., 2019; Troccoli et al., 2015). ~~in similar agroecosystems.~~ ~~Nonetheless, initial~~In this paper, short-term effects on soil physical ~~parameter~~ properties can be detected in some situations by measuring BD, PR, and soil hydraulic properties. Driven primarily by tillage intensity, lower BD values were found in the ~~tilled~~ 0-30 cm layer of both CT and MT despite being the latter tilled only in the top 15 cm, confirming the~~. Furthermore, the results highlighted that the magnitudes of BD values at the deeper levels of soil tillage (30 cm ploughing) were similar to those at shallower tillage depths (≤ 15 cm). This~~ finding ~~is consistent with work by~~of Guan et al. (2014). According to the USDA Natural Resources Conservation Service (1996), a BD value of 1.55 g cm^{-3} in silty loam soils represents a threshold above which plant growth may be hindered. In this study, this threshold was exceeded, especially at depths below the tilled layer in the first survey (2018), which may be linked to the presence of a plough pan that arose due to repeated soil tillage to the same depth. In a similar agroecosystem, the presence of a plough pan was detected when geophysical and direct assessment methods were combined by Piccoli et al. (2020). Specifically, the authors found the plough pan responsible for shallower and greater lateral development of the root apparatus in winter cereals, although it seemed not to affect spring crops (maize, soybean)~~ (Piccoli et al., 2021)~~. During the last survey of the study ("Autumn 2020"), both MT and NT exhibited lower BD values beneath the ~~tilled~~ 0-30 cm layer. This observation suggests that reduced tillage systems may diminish the strength of a pre-existing hard-pan, ~~as~~ which is a key goal~~s~~ of CA (Troccoli et al., 2015). ~~Alternatively, given that CC adoption affected BD to only a limited extent, it is quite possible that a longer time period is required to see more change as Blanco-Canqui et al. (2011) observed in similar pedological conditions. The complexity of the effect of CC on BD as the present study revealed in its 2020 contrasting results from before and after the main cropping season. In fact, seasonal BD changes reported in the literature are generally linked first to meteorological and biological factors (Hu et al., 2012) and secondarily to the time interval after tillage (Ellert and Bettany, 1995; Wendt and Hauser, 2013).~~

~~Permeability~~ Penetration resistance results confirmed some BD trends. They showed lower average values when associated ~~to~~ with ~~wide~~ differences in tillage intensity (i.e., ploughing *vs* no-tillage). These results agreed with some authors ~~which reported~~showing an increase of PR and BD in the first year of conversion to CA (Trevini et al., 2013) and disagreed with others, ~~according which~~who reported that CA can reduce these values since its adoption (Blanco-Canqui and Ruis, 2020; Parihar et al., 2016; Singh et al., 2016). It is worth noting that MT resulted as the tillage with the highest PR values, which contrasted with data obtained in similar pedological conditions, such as Sharratt et al. (2012). ~~As for BD, inconsistent CC results were also found for PR. In general, WW seemed to affect soil strength positively, while TR had either a negligible or negative effect on soil strength. Whereas the well-documented positive effects of Graminaceous CC on soil physical parameters were expected (Diacono et al., 2019), the inconsistent results for TR were not. In fact, these results were at odds with the reason taproot species were first introduced and adopted as cover crops – for their beneficial effects on soil physical qualities, and soil compaction alleviation, in particular (Toom et al., 2019; Wittwer and van der Heijden, 2020).~~The analyses of Ks and S highlighted enhanced water infiltration under NT management; moreover, the effects seemed stronger during the second survey (2020). These results seemed to contrast with BD and PR evidence obtained during the same period (i.e., increased density and strength under NT). Indeed BD, PR and Ks are usually linked to each other as a lower soil porosity is expected to reflect also in greater BD and PR and lower Ks. However, controverisial results on these properties are already present in the literature (Blanco-Canqui and Ruis, 2020; Castellini et al., 2020; Strudley et al., 2008). In fact, some studies (e.g., Lipiec et al., 2006; Pagliai et al., 2004) have found how despite a lower total porosity, the presence a few of biopores from root decomposition and earthworm activity in NT might alleviate soil compaction (i.e., graeter BD and PR) by promoting preferential flow through macropores, that resulted in icrease Ks. On the contrary, other studies (e.g., Kahlon et al., 2013; Vogeler et al., 2009) have suggested that the loss of porosity under NT and the increased BD and PR may not improve water infiltration (e.g., Ks).

The CC adoption in the present study evidenced limited impact on studied physical parameters. Blanco-Canqui et al. (2011) highlighted how longer period may be required to exploit their benefits ~~related to CC~~.

Moreover, the effect of CC on soil physical properties is complex and linked to seasonal changes, meteorological conditions and biological factors (Hu et al., 2012). ~~The inconsistent results of CC on BD and PR may stem from some methodological issues as well. One such issue is that the sampling area on which the measurements were taken was limited to 39 cm^2 for BD and 2 cm^2 for PR, whereas the effect from the apparatus of a taproot cover crop that can only be observed on a larger scale. Another factor may be the various values that authors have suggested as being the PR threshold (de Moraes et al., 2014b). It~~

~~can be hypothesised that under real field conditions, roots can circumvent harder zones if biopores are present. In NT in particular, the high presence of earthworms and the pores left by CC roots—possibly even weed roots—could permit subsequent-crop root penetration into the soil, despite a high average PR resistance (Hirth et al., 2005).~~

~~The analyses of Ks and S highlighted enhanced water infiltration under no-tillage management; moreover, the effects seemed stronger during the second survey. Initially, these results seemed to contrast with BD and PR evidence obtained during the same period. Usually, high BD and PR values are linked to lower soil porosity, so lower Ks values were expected relative to those observed. However, contrasting results on the effects of reduced tillage on Ks also appear in the literature (Blanco-Canqui and Ruis, 2020; Castellini et al., 2020; Strudley et al., 2008). Indeed, some studies (e.g., Lipiec et al., 2006; Pagliai et al., 2004) have found how the presence of biopores from root decomposition and earthworm activity might alleviate soil compaction by promoting preferential flow through macropores, while other studies (e.g., Kahlon et al., 2013; Vogeler et al., 2009) have suggested that the loss of macroporosity under no-tillage may not sustain water infiltration. The result contrasts such as those observed across the different soil coverings may be influenced by length of the monitoring period, length of the transition period, and/or issues of scale. A marginal effect that faded during the main cropping season reported amongst the different CC has also been reported by~~ Wagger and Denton (1989) previously justified CCs ineffectiveness with their ~~. It likely relates to the~~ limited potential ~~of CC t~~of ~~promote~~ promoting well-developed pore networks. In this study, WW seemed to reduce soil PR confirming the positive effect of CC on soil strength as observed by Diacono et al. (2020). On the contrary, TR had either a negligible or a negative effect on soil properties with respect to bare soil. Taproot species as TR were first introduced and adopted as CCs for their beneficial effects on soil physical properties, and soil compaction alleviation, in particular (Toom et al., 2019; Wittwer and van der Heijden, 2020). The inconsistent results of CC on BD and PR may stem from some methodological issues as well. One such issue is that the sampling area on which the measurements were taken was limited to 39 cm^2 for BD and 2 cm^2 for PR, whereas the effect from the apparatus of a taproot cover crop can only be observed on a larger scale. It can be hypothesised that under real field conditions, roots can circumvent harder zones if biopores are present. In NT in particular, the high presence of earthworms and the pores left by CC roots—possibly even weed roots—could permit subsequent-crop root penetration into the soil, despite a high average PR resistance (Hirth et al., 2005). Therefore, the sampling size may also have caused an effect; for example, CC could exert an effect observable only on a large area (e.g., sub-metric scale), even though most soil analyses (e.g., BD) are performed at smaller scales (e.g., centimetre-scale) (Piccoli et al., 2019). In this study, the presence of a BD-PR correlation capable of depiction only in the 0.5-2.5 MPa and 1.33-1.80 g cm^{-3} ranges may suggest that in lower density soil profiles (i.e., BD<1.8 g cm^{-3} and PR<2.5 MPa), soil structure dynamics might be governed by a centimetre scale due to a homogeneous pore network. On the contrary, higher density (e.g., BD>1.8 g cm^{-3} and PR>2.5 MPa) soils might be characterized by high anisotropic porosity, in which the presence/absence of few macropores (e.g., cracks, biopores) may rule structure dynamics and soil functions in the form of water infiltration and/or gas exchanges (Piccoli et al., 2017a, 2019). We hypothetized that the inconsistent results seen in NT and CC systems were also probably caused by a scale issue. Indeed, NT evidenced soil compaction and satisfactory water infiltration simultaneously, likely due to the presence of vertically-oriented biomacropores and greater pore connectivity (Piccoli et al., 2017b) that are visible only with soil properites measurements involving sub~~m~~-metric scale.

Finally, ~~Seasonal variability could also have affected soil properties and mask CC effects. Effects from the length of the transition period after conversion from conventional to CA have yet to be fully characterized, although increased soil strength is often observed in the short term.~~ Kay and Vanden Bygaart (2002) have identified three distinct phases following CA adoption: 1) short-term phase (months): soil compaction and fragmentation is expected from tillage absence and traffic load; 2) medium-term phase (years): greater biological activity (e.g., higher numbers of earthworms) promotes the formation of vertically-oriented bio-macropores, which in turn, alleviates soil strength; 3) extended-term phase (decades): different distributions of soil organic matter stabilize soil structure and fulfil ecosystem servicing needs. The studied soil under NT+CC were in the transition period during the experimentation and, despite experiencing some soil compaction-related issues, showed improved functionality (e.g., water infiltration) with respect to traditional management suggesting that further benefits in terms of soil quality and health are expected during the next years.

~~In addition, sampling size may also have caused an effect; for example, CC could exert an effect observable only on a large area (e.g., sub-metric scale), even though most soil analyses (e.g., bulk density~~BD~~) are performed at smaller scales (e.g., centimetre-scale) (Piccoli et al., 2019).~~

~~In this study, the presence of a BD-PR correlation capable of depiction only in the 0.5-2.5 MPa and 1.33-1.80 g cm^{-3} ranges may suggest that in lower density soil profiles (i.e., BD<1.8 g cm^{-3} and PR<2.5 MPa), soil structure dynamics might be governed by a centimetre scale due to a homogeneous pore network. On the contrary, higher density (e.g., BD>1.8 g cm^{-3} and PR>2.5 MPa) soils might be characterized by low anisotropic porosity, in which the presence/absence of few macropores (e.g., cracks, biopores) may rule structure dynamics and soil functions in the form of water infiltration and/or gas exchanges (Piccoli et al., 2017a, 2019). The inconsistent results seen in no-tillage systems probably were caused by a scale issue as well. Indeed, NT evidenced soil compaction and satisfactory water infiltration simultaneously, likely due to the presence of vertically-oriented biomacropores and greater pore connectivity (Piccoli et al., 2017b). Consequently, both CC and NT systems are likely to produce more heterogeneous soil structure as compared with tilled soils.~~

Conclusions

This study proved that during the transition period from conventional to conservation agriculture some compaction issues can be linked to no-tillage when monitoring is performed with traditional small-scale physical methods (e.g., ~~bulk density~~BD, ~~penetration resistance~~PR) due particularly to a high soil structure heterogeneity. To correctly evaluate the effects of CA on soil function and soil compaction threat, ~~therefore, the use of larger-scale measurements, such as~~ the ~~double~~ double-ring infiltrometer, might be preferable ~~in no-tillage managements~~ to overcome the inherent problems of higher spatial variability at the micro-scale and to consider soil function as a whole. The fibrous root apparatus of *Poaceae* species seems a promising cover crop to enhance soil physical qualities in the no-tillage systems of Northeast Italy, even in the short term.

Moreover, Graminaceous, such as winter wheat, are commonly cash crops in this study area and their agronomic management (e.g., sowings) is easily implemented by farmers. For these reasons, we ~~This seems to~~ partially reject the ~~initial~~ starting hypothesis since drawbacks related to ~~: the negative impact of~~ reduced tillage (i.e., soil compaction) were not clearly alleviated by the ~~system was not evident in the first conversion year, and the~~ adoption of TR ~~seemed to have a little impact on soil physical properties~~during the transition period. However, the longer period required for taproot cover crop (e.g., tillage radish), and no-till systems alike, to exploit its ecosystem services fully requires their evaluation at a larger scale. One of the future challenges that the agronomic community will face is the termination of cover crops, especially in light of pesticide reduction, and/or the selection of winter-killed species to meet the sustainable development goals of the 2030 Agenda.

Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author contributions. Conceptualization, A.B.; methodology, I.P., A.B.; formal analysis, F.S.; investigation, F.S. and R.P.; Resources, R.P.; data curation, F.S. and R.P.; writing—original draft preparation, F.S. and I.P.; writing—review and editing, F.S., I.P., R.P. and A.B.; visualization, F.S.; supervision, A.B. All authors have read and agreed to the published version of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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