Soil & Tillage Research 232 (2023) 105761

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Long-term impacts of repeated cover cropping and cultivation approaches on subsoil physical properties

J. Martlew[a,b], W. Otten[a], N. Morris[b], S. De Baets[a,c], L.K. Deeks[a,*]

[a] Cranfield University, School of Water, Energy and Environment, MK43 0AL, UK
[b] NIAB, Cambridge CB3 0LE, UK
[c] KU Leuven, Research Coordination Office, Schapenstraat 34 - bus 5100, 3000 Leuven, Belgium

ARTICLE INFO

Keywords:
Subsoil
Soil properties
Cover crop
Cultivation

ABSTRACT

The intensification of arable agriculture has resulted in an increase in vehicle wheel load and the intensity of field operations, which has increased the risk and incidence of degradation in physical properties of the uncultivated subsoil layer. Biopores generated by the long-term, repeated use of specific cover crops within an arable rotation has been suggested as an approach to improve subsoil physical properties. Therefore, this paper aimed to determine the impact of long-term repeated cover cropping and the interaction of rotation treatments with different cultivation approaches on subsoil physical properties. Data was collected at the NIAB 'Sustainable Trial for Arable Rotations' long-term, rotation and cultivation field experiment established in 2006. Rotation treatments comprised a brassica cover crop alternated annually with winter wheat (ALTCC) compared to continuous winter wheat (CWW). Cultivation treatments comprised PLOUGH (250 mm depth), and non-inversion cultivation at 250 mm (DEEP) and 100 mm (SHALLOW) depths. Penetration resistance and volumetric soil moisture were collected at bi-monthly intervals during the 2018/19 growing season. Undisturbed soil cores were collected for laboratory analyses of soil water retention, water stable aggregates, root morphology digital scanning and biomass, and X-ray computed tomography (CT). Results showed that treatment ALTCC combined with SHALLOW, resulted in lower penetration resistance and increased moisture in the subsoil. This increased subsoil moisture persisted later into the season compared to the control. SHALLOW increased subsoil water retention, improved subsoil root morphology and increased subsoil porosity. Benefits from treatment ALTCC were not observed where combined with higher intensity, deeper cultivation. Overall, the combination of treatments ALTCC with SHALLOW, produced significant benefits to subsoil physical properties.

1. Introduction

Pursuit of greater agricultural efficiency has driven increases in field management intensity, which has increased the risk of subsoil degradation (Keller et al., 2019; Schjønning et al., 2018). Risk modelling suggests that c. 40% of European subsoils may already be degraded, with agricultural management a significant driver (Brus and van den Akker, 2018; Schneider, Don, 2019a; Schjønning and Thorsoe, 2019). This is of concern because subsoil degradation is known to be highly persistent over time (Etana and Håkansson, 1994; Jones et al., 2003), negatively impacts soil properties such as hydraulic conductivity (Arvidsson, 2001; Berisso et al., 2012; Lipiec et al., 2003; Poodt et al., 2003; Rickson et al., 2015; Trautner et al., 2003) and may reduce crop performance (Håkansson, 1994; Håkansson and Reeder, 1994; McKenzie et al., 2009).

Management practices targeted to improve subsoil physical properties should aim to improve water, gas and root movement by creating fissuring and cracking of the subsoil, without excessive disruption and weakening of the soil profile (Spoor et al., 2003). Mechanical cultivation may have a positive effect but leaves the soil vulnerable to recompaction through subsequent field operations (Chamen et al., 2003; Olesen and Munkholm, 2007; Schneider, Don, 2019b).

Exploiting characteristics of specific cover crop roots has been proposed as an alternative method to mechanical cultivation to improve soil physical properties (Bengough et al., 2011; Cresswell and Kirkegaard, 1995; Pulido-Moncada et al., 2020). Roots can improve soil physical properties by creating pore space and exploiting existing pores (Chen and Weil, 2010; Clark et al., 2003). Colonisation of pre-existing 'biopores' may be an approach by arable crops to cope with degraded soil

---

* Correspondence to: Cranfield University, School of Water, Energy and Environment, Building 52a, MK43 0AL, UK.
E-mail address: l.k.deeks@cranfield.ac.uk (L.K. Deeks).

https://doi.org/10.1016/j.still.2023.105761
Received 27 June 2022; Received in revised form 3 April 2023; Accepted 8 May 2023
Available online 2 June 2023

layers (Atkinson et al., 2020). Channels created by roots through compacted subsoil have been shown to improve water and gas transport (Lipiec and Hatano, 2003; Uteau et al., 2013), increase crop root depth through pore recolonisation (Dexter, 1991; Kautz, 2015; Landl et al., 2019; Perkons et al., 2014) and to be resistant to recompaction (Schaffer et al., 2008; Schaffer et al., 2007). Deep-rooted brassicas (Clark et al., 2003; Materechera et al., 1992; Williams and Weil, 2004) and some graminaceous species (Burr-Hersey et al., 2017; McKenzie et al., 2009) have demonstrated potential to modify soil structure but the application to subsoil at field-scale requires further investigation due to lack of published evidence (Carof et al., 2007; Frelih-Larsen et al., 2018; Storr et al., 2019).

Cultivation is directly linked to subsoil degradation risk (Alakukku et al., 2003). Reducing cultivation intensity has been shown to improve the structural stability of the soil profile and reduce the risk of subsoil compaction (Chamen et al., 2003; Hernanz and Sanchez-Giron, 2000; Sommer, 2000). Although the impact of cultivation on subsoil compaction has been well established (Spoor et al., 2003), the long-term interaction of cultivation approach and cover cropping on subsoil degradation in the field has not been adequately investigated.

The aim of this paper is to determine the impact of long-term repeated cover cropping and the interaction of rotation with different cultivation approaches on subsoil physical properties. The hypothesis that repeated, alternate season cover crop rotation combined with reduced cultivation intensity, will decrease long-term subsoil physical degradation compared to continuous cereal rotation and conventional cultivation was tested.

2. Materials and methods

2.1. Experimental site and design

The NIAB 'Sustainable Trial for Arable Rotations' (STAR) project is a long-term, field-scale rotation and cultivation experiment, established in 2006 at Stanway Farm, Suffolk, UK (52°8′17.50°N, 1°11′27.21°E). The experiment is a factorial design, replicated over three blocks with plots of 36 × 36 m (l x w). Treatments are applied using commercial scale equipment, on a Beccles/Hanslope (Stagnosol/Cambisol) soil series (Hodge et al., 1984).

The full experiment comprised four rotation and four cultivation treatments ($n = 48$ plots) as detailed in Stobart and Morris (2011). Two rotation and three cultivation treatment combinations ($n = 6$ plots) were selected from the full experiment for the purposes of this paper (excluding the 'managed' farmer-led treatments that were not controlled treatments), which were triple replicated over three blocks ($n = 18$ plots total).

Historic application of rotation and cultivation treatments are outlined in Table 1. Rotation treatments consisted of continuous winter wheat (*Triticum aestivum*) (CWW), where winter wheat was grown every season, and an alternate season mustard brassica (*Brassica* spp.) cover crop (ALTCC), where a cover crop was alternated annually with winter wheat (*Triticum aestivum*). Annual cultivation treatments consisted of plough (PLOUGH) (inversion cultivation, 250 mm depth), deep cultivation (DEEP) (non-inversion cultivation using a combination of tines and discs, 250 mm depth) and shallow cultivation (SHALLOW) (non-inversion cultivation using a combination of tines and discs, 100 mm depth). One rotation and one cultivation treatment were applied to each plot following the triple replicated, factorial design. Treatments will be referred to by their singular nomenclature (e.g. ALTCC or PLOUGH) and/or their combined nomenclature (e.g. PLOUGH ALTCC) depending on the context.

The date of rotation and cultivation treatment application varied annually dependent on soil and climatic conditions but always occurred during the autumn period (Sep – Nov). Rotation treatment cover crops were terminated in early summer (May – Jun) and the plots left fallow until the next autumn rotation treatment was applied (Sep – Nov). Therefore, the ALTCC represented a full season cover crop that replaced a cash crop in the rotation. Permanent tramlines were used for the application of agrochemicals and fertilisers. These were established through each plot at a 90° angle to the direction of treatment application.

Treatment ALTCC was substituted with a perennial herbal ley (HL) from September 2018. The existing ALTCC treatment plots were non-inversion cultivated to 100 mm depth and the HL treatment was established 3rd September 2018. No further cultivations took place on these plots, but cultivation treatments continued as before for the CWW treatment. The full list of field operations and HL treatment species list are included in Appendix A. The treatment that combines both ALTCC and HL is referred to as ALTCC.

The definition of three specific soil layers is useful when discussing subsoil compaction: topsoil, pan layer and uncultivated subsoil (Alakukku et al., 2003). The topsoil represents the managed layer that extends from the soil surface to the maximum depth of annual cultivation. Immediately below the topsoil, a narrow and compacted pan layer can develop. Below either the topsoil or the pan layer is the uncultivated subsoil. Typically, the subsoil is not disturbed by annual cultivation and is only loosened during exceptional field operations such as mole draining or periodic deep cultivations such as subsoiling (Alakukku et al., 2003).

2.2. Field monitoring methods

Data was collected throughout the 2018/2019 growing season and collection was carried out at approximately bi-monthly intervals (Nov 2018 – Aug 2019). Methods were chosen for their applicability to soil properties and the function of soil to support agriculture (Whalley et al., 2008).

Penetration resistance (PR) was collected using a manually operated digital penetrometer (Eijelkamp, Digital Penetrologger V.6.13). Ten randomised penetrations were collected for each plot to 600 mm depth using a 1.2 cm^2 30° cone. Measurements were obtained in Nov 2018 and Jan, Mar and May 2019. Volumetric soil moisture (VSM) was measured

Table 1
Rotation and cultivation treatment annual summary and definitions. Winter wheat – WW; cover crop – CC.

Annual rotation treatment application													
	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
CWW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW	WW
ALTCC	CC	WW	CC	WW	CC	WW	CC	WW	CC	WW	CC	WW	HL
Rotation treatments													
WW	Winter wheat (*Triticum aestivum*)												
ALTCC	Mustard brassica (*Brassica* spp.) cover crop												
HL	Perennial herbal ley species mixture (full species list Appendix A)												
Cultivation treatments													
PLOUGH	Inversion ploughed to depth 250 mm annually												
DEEP	Non-inversion cultivated using disc and tine combination to depth 250 mm annually												
SHALLOW	Non-inversion cultivated using disc and tine combination to depth 100 mm annually												

using a capacitance probe (Delta-T Devices, Profile Probe PR1) with sensors at 150, 250, 350, 450 and 650 mm depths (calibration slope offset 1.6, slope 8.4). Each plot had one access tube installed, located 5 × 5 m inside the southwest plot corner. Parallel to the PR data, VSM was collected in Mar, May and additionally in Aug 2019.

Weather data was collected from an on-site weather station and is included in Fig. C1, Appendix C.

2.3. *Undisturbed soil core methods*

One undisturbed soil core (800 ×84 mm, h x d) was collected from each plot ($n = 18$) (Han 2019) using a pneumatic cylinder auger (Eijelkamp, Soil Column Cylinder Auger). Cores were divided into four layers (200 ×84 mm, h x d) and refrigerated at 5 °C within 24 hrs of extraction. Triple replicated subsamples for each method were collected using the same core orientation and same volume from each core section. Methods were chosen to reflect a broad range of physical properties that have been used previously to characterise physical degradation (Rabot et al., 2018).

Soil texture (hand method; BSI, 1994), organic matter (%) (loss on ignition (BSI, 2000)) and bulk density (g cm^{-3}) (drying for 24 h at 105 °C; BSI, 2013) were determined for each soil layer. No significant differences were found between rotation or cultivation treatments in bulk density or organic matter (Table 2). Soil texture transitioned from sandy loam/sandy clay loam at 0 – 200 mm depth to an increased clay content with depth. Chalk fragments are present from 200 mm and increased in frequency with depth (Appendix C).

Soil water retention (cm^3 cm^{-3}) was determined using a combination of sand table and pressure plate apparatus (BSI, 2019). Soil water retention at potentials of 0 kPa (saturation), 5 and 10 kPa (field capacity), 200 kPa (easily available water) and 1500 kPa (permanent wilting point) were determined.

Water stable aggregates (WSA) (%) were determined using the modified Yoder method (Eijelkamp, Wet Sieving Apparatus) (Kemper and Rosenau, 1986). Air dried aggregates (1 – 2 mm size fraction) were moistened using a fine mist sprayer in a 0.25 mm mesh sieve, agitated for 3 min in distilled water, followed by continuous agitation in a 2 g l^{-1} sodium hexametaphosphate solution ($(NaPO_3)_6$). Any remaining sand particles were discarded, leachates oven dried (24 hrs at 110 °C) and mass recorded. The WSA was calculated as in Eq. 1.

$$\text{WSA}\ (\%) = (Msoil^a/(Msoil^a + (Msoil^b))*100 \tag{1}$$

$Msoil^a$ – mass of oven dried 3-minute distilled water fraction.

$Msoil^b$ – mass of oven dried continuous agitation 2 g l^{-1} sodium hexametaphosphate solution fraction (minus 0.2 g sodium hexametaphosphate solute mass correction).

Table 2

Bulk density (BD) (g cm^{3-1}) and soil organic matter (OM) (%) over depth layers. Continuous winter wheat – CWW; alternate cover crop – ALTCC; P – PLOUGH; D – DEEP; S – SHALLOW. SE - standard error of the means for comparison within depth category.

Depth (mm)							
0–200		200–400		400–600		600–800	
BD	OM	BD	OM	BD	OM	BD	OM
1.47	3.91	1.54	2.80	1.48	2.40	1.57	1.94
1.47	4.14	1.55	2.67	1.54	3.02	1.54	2.42
1.43	4.17	1.56	2.24	1.55	2.62	1.58	2.07
1.50	4.01	1.55	2.80	1.54	2.68	1.53	2.62
1.40	4.31	1.52	3.05	1.48	2.86	1.62	1.93
1.43	4.01	1.56	2.13	1.55	2.45	1.60	1.67
0.05	*0.56*	*0.07*	*0.58*	*0.06*	*0.45*	*0.08*	*0.46*
1.46	4.07	1.55	2.57	1.52	2.68	1.56	2.14
1.44	4.11	1.55	2.66	1.52	2.66	1.58	2.07
0.03	*0.33*	*0.04*	*0.33*	*0.04*	*0.26*	*0.05*	*0.27*
1.48	3.96	1.55	2.80	1.51	2.54	1.55	2.28
1.44	4.22	1.53	2.86	1.51	2.94	1.58	2.18
1.43	4.09	1.56	2.19	1.55	2.54	1.59	1.87
0.04	*0.40*	*0.05*	*0.41*	*0.04*	*0.32*	*0.06*	*0.33*

Root were extracted from the soil by washing over a 1 mm sieve (do Rosario et al., 2000). All root material was optically scanned (Reagent Instruments, SDT4800) at 400 dpi. Mean root diameter and total root length (mm) were measured using WinRHIZO root morphology software (Reagent Instruments, WinRHIZO Pro). Root material was then oven dried (24 hrs at 65 °C) to determine total dry root biomass (g).

Soil samples from the 200 – 400 mm layer were selected for X-ray computed tomography (CT), which was carried out at the University of Nottingham Hounsfield Facility, UK. Subsamples of 30 × 30 mm (h x d) were scanned using Pheonix V|tome|X m X-Ray scanner (GE Measurement and Control Solutions) at 170 kV 150 µA. A total of 2998 projections were collected at 28 µm voxel resolution. Images were reconstructed at 32-bit (Pheonix Datosx 2, GE Measurement and Control Solutions) and processed to 8-bit.bmp stacks (VG Studio Max 2.2.5., Volume Graphics GmbH). Stacks were segmented into solid and pore (%) then analysed using Minkowski functionals to obtain measures of pore volume (%), connected pore volume (%), pore-solid surface area (voxels) and connected pore surface area (voxels) (Falconer et al., 2012; Houston et al., 2013; Vogel et al., 2010). Pore size distribution (n) was summarised in Fiji open-source image analysis software (Schindelin et al., 2012) using the BoneJ (Doube et al., 2010) plugin 'particle analyser tool' (Houston et al., 2017). Pore size distribution were split into classes of 28 – 1000 µm (meso - macropores), 1000 – 2000 µm (macropores), 2000 – 5000 µm (macropores) and > 5000 µm (large macropores/soil cracks).

2.4. *Statistical analyses*

All results were analysed using IBM SPSS (IBM SPSS Statistics, V26). All data was checked for normality by plotting histogram and quantile-quantile plots. Root biomass and pore size distribution were $\log_{10}$ transformed to normalise the data distribution. Factorial ANOVA was used to analyse all data without a depth factor and repeated measures factorial ANOVA was used to analyse all data that had depth as a factor (treating depth as a within-subjects variable). Where significant effects were observed, these were followed by a Fischer's least significant difference (LSD) test. Error bars represent the standard error of the means for the treatment comparison and/or depth category discussed (SE). All tests were conducted at the 5% significance level (P).

3. Results

3.1. *Field monitoring results*

3.1.1. *Penetration resistance*

Within the working depth of cultivation implements, SHALLOW CWW had a significantly ($P < 0.05$) higher PR compared to DEEP CWW at 0 – 350 mm depth and PLOUGH CWW at 0 – 300 mm depth (Fig. 1.1, 1.2, 1.3). Similar but less clear trends occurred with ALTCC rotation, where SHALLOW ATLCC had significantly ($P < 0.05$) higher PR compared to DEEP ALTCC at 200 – 350 mm depth (Fig. 1.1, 1.2), and PLOUGH ALTCC had significantly ($P < 0.05$) higher PR compared to DEEP ALTCC at 200 – 300 mm depth (Fig. 1.1). PLOUGH CWW had significantly ($P < 0.05$) higher PR compared to DEEP CWW at 250 – 600 mm depth (Fig. 1.1, 1.3, 1.4).

ALTCC had significantly ($P < 0.05$) higher PR compared to CWW at 0 – 250 mm depth when combined with both PLOUGH and SHALLOW cultivation treatments Nov 2018 (Fig. 1.1) and all cultivation treatments Jan/Mar/May 2019 (Fig. 1.3, 1.4). CWW had significantly ($P < 0.05$) higher PR compared to ALTCC at 350 – 600 mm depth when combined with PLOUGH and DEEP (Fig. 1.2), SHALLOW (Fig. 1.3) and PLOUGH (Fig. 1.4).

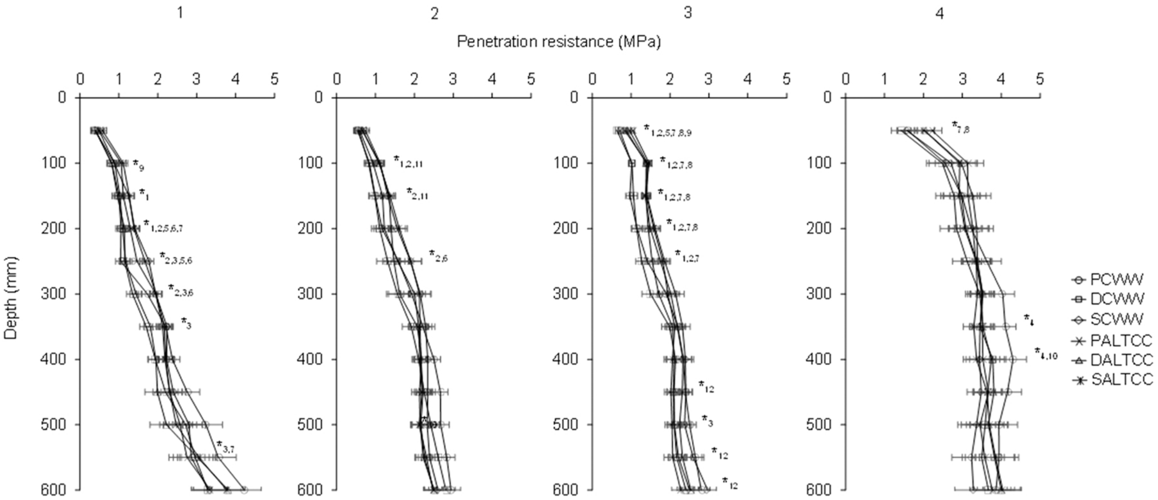


Fig. 1. Penetration resistance (MPa) rotation and cultivation treatment interaction over depth 1) Nov 2018 2) Jan 2019 3) Mar 2019 4) May 2019 5) mean all collection dates. ALTCC – alternate cover crop, CWW – continuous winter wheat, P – plough cultivation, D – deep cultivation, S – shallow cultivation. Significant differences ($P < 0.05$) correspond to the following: 1 S CWW>P CWW, 2 S CWW>D CWW, 3 P CWW>D CWW, 4 P CWW>S CWW, 5 P ALTCC>D ALTCC, 6 S ALTCC>D ALTCC, 7 P ALTCC>P CWW, 8D ALTCC>D CWW, 9 S ALTCC>S CWW, 10 P CWW>P ALTCC, 11D CWW>D ALTCC, 12 S CWW>S ALTCC. Error bars represent standard error of the mean between treatments at each depth category (for full interactions see Appendix D (Fig. D1)).

3.1.2. Volumetric soil moisture

SHALLOW CWW had significantly ($P < 0.05$) higher VSM compared to PLOUGH CWW at 250 – 350 mm depth (Fig. 2.1 and 2.3) and compared to DEEP CWW at 150 mm depth (Fig. 2.3). SHALLOW ALTCC had significantly ($P < 0.05$) higher VSM compared to PLOUGH ALTCC at 150 mm depth (Fig. 2.1).

3.2. Undisturbed soil core results

3.2.1. Soil physical properties

Significant differences for WSA were only observed in depth 0 – 200 mm. SHALLOW had significantly higher WSA compared to PLOUGH at 0 – 200 mm depth ($P = 0.02$; $SE = 7.03$) (Table 3). Where interaction was compared over depth, DEEP ALTCC had significantly higher WSA compared to PLOUGH ALTCC at 0 – 200 mm depth ($P = 0.03$; $SE = 9.95$) (Table 3).

Soil samples from the 200 – 400 mm layer were selected for X-ray computed tomography (CT) due to the observation of a compacted layer in the PR data (Section 3.1.1). SHALLOW ALTCC had significantly higher pore volume (%) compared to SHALLOW CWW ($P = 0.05$; $SE = 0.66$) and DEEP ALTCC ($P = 0.04$; $SE = 0.66$) (Table 4). SHALLOW ALTCC also had significantly higher pore surface area (voxels) compared

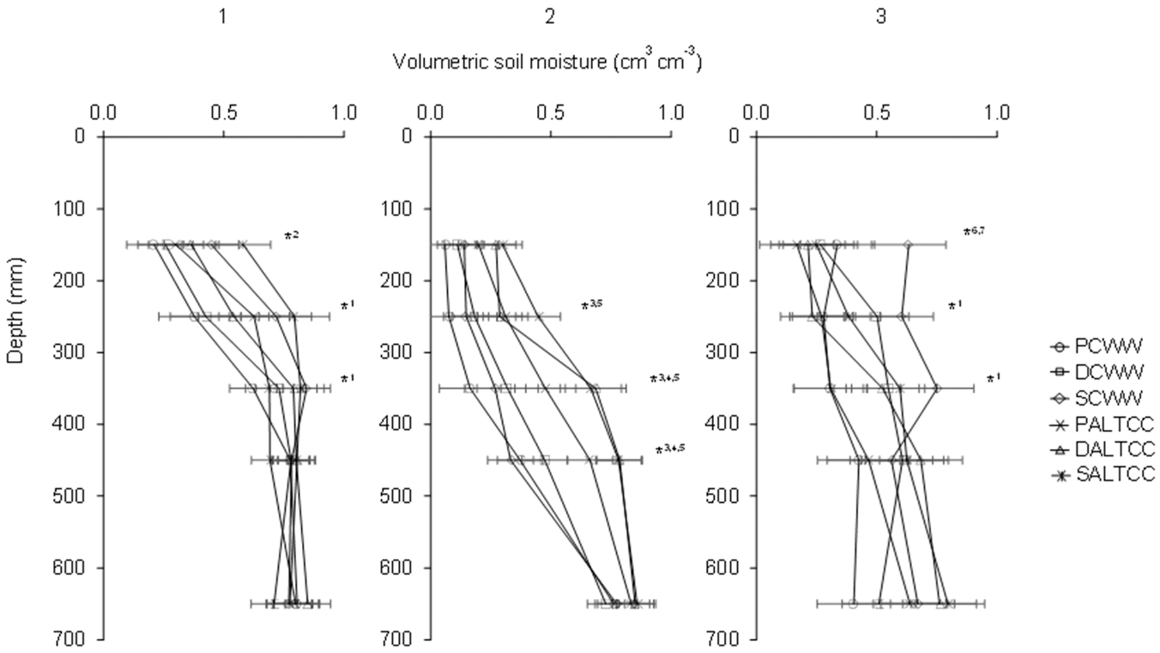


Fig. 2. Volumetric soil moisture ($cm^3\ cm^{-3}$) rotation and cultivation treatment interaction over depth 1) Mar 2019 2) May 2019 3) Aug 2019 4) mean all collection dates. ALTCC – alternate cover crop, CWW – continuous winter wheat, P – plough cultivation, D – deep cultivation, S – shallow cultivation. Significant differences ($P < 0.05$) correspond to the following: 1 S CWW>P CWW, 2 S ALTCC>P ALTCC, 3 P ALTCC>P CWW, 4D ALTCC>D CWW, 5 S ALTCC>S CWW, 6 S CWW>S ALTCC, 7 S CWW>D CWW, 8SALTCC>DALTCC. Error bars represent standard error of the mean between treatments at each depth category (for full interactions see Appendix E (Fig. E1)).

Table 3

NIAB STAR experiment treatment means over depth layers for water stable aggregates (WSA) (%). Continuous winter wheat – CWW; alternate cover crop – ALTCC; P – PLOUGH; D – DEEP; S - SHALLOW. Lowercase letters represent significant differences ($P \leq 0.05$) within a section e.g.^{a,b,c}. SE - standard error of the means for comparison within depth category.

Depth (mm) Treatment	0 – 200	200–400	400–600	600–800	Mean
PCWW	74.2	83.7	80.6	80.4	79.7
DCWW	77.6	89.4	89.5	74.8	82.8
SCWW	93.7	91.1	83.9	82.1	87.7
PALTCC	66.1^{a}	79.7	90.0	75.2	77.8
DALTCC	90.7^{b}	92.4	89.0	71.8	86.0
SALTCC	85.9	91.1	76.2	79.1	83.1
SE	10.0	*8.9*	*6.8*	*8.1*	*4.6*
CWW	81.8	88.0	84.7	79.1	83.4
ALTCC	80.9	87.7	85.1	75.4	82.3
SE	*5.8*	*5.1*	*3.9*	*4.9*	*2.7*
PLOUGH	70.2^{a}	81.7	85.3	77.8	78.7
DEEP	84.1	90.9	89.3	73.3	84.4
SHALLOW	89.8^{b}	91.1	80.1	80.6	85.4
SE	*7.0*	*6.3*	*4.8*	*6.0*	*3.3*

Table 4

Undisturbed soil core X-Ray CT analyses results (200 – 400 mm depth). Continuous winter wheat – CWW; alternate cover crop – ALTCC; P – PLOUGH; D – DEEP; S - SHALLOW. Significant differences ($P \leq 0.05$) are organised by column and section. Lowercase letters without parentheses represent differences within a section e.g.^{a,b,c}, and uppercase letters, numbers and symbols with parentheses represent significant differences ($P \leq 0.05$) between sections e.g.$^{(A/B),(1/2),(*/**)}$. SE - standard error of the means for comparison within depth category.

Treatment	Pore volume (%)	Connected pore volume (%)	Pore surface area (voxels)	Connected pore surface area (voxels)
PCWW	21.9	21.1	4.61	12.45
DCWW	20.6	27.9	4.02	16.59
SCWW	20.1$^{(A)}$	18.8	6.19	8.74
PALTCC	28.4	37.3	4.09	12.04
DALTCC	18.6^{a}	24.1	2.97^{a}	8.90
SALTCC	34.2$^{b\ (B)}$	30.6	5.86^{b}	11.76
SE	*0.7*	*11.8*	*1.09*	*6.90*
CWW	20.8	22.6	4.94	12.59
ALTCC	27.1	30.7	4.31	10.90
SE	*0.4*	*6.8*	*0.63*	*3.99*
PLOUGH	25.1	29.2	4.35^{a}	12.25
DEEP	19.6	26.0	3.49^{a}	12.75
SHALLOW	27.2	24.7	6.03^{b}	10.25
SE	*0.5*	*8.4*	*0.77*	*4.88*

to DEEP ALTCC (P = 0.02; SE = 1.09) (Table 4). SHALLOW cultivation treatment had significantly higher pore surfaces area (voxels) compared to both PLOUGH and DEEP (P = 0.05 and <0.01 respectively; SE = 0.77) (Table 4).

Similarly, treatment SHALLOW had a positive impact on pore frequency. SHALLOW had a significantly higher pore frequency in the 28 – 1000, 1000 – 2000 and 2000 – 5000 µm categories compared to DEEP (P = 0.01, <0.01 and <0.01; SE = 1.41, 1.31 and 1.32 respectively) (Fig. 3). SHALLOW CWW had significantly more pores in all pore size categories compared to PLOUGH CWW and DEEP CWW (28 – 1000 µm P = 0.03 and <0.01; SE = 1.63, 1000 – 2000 µm P = 0.03 and <0.01; SE = 1.47, 2000 – 5000 µm P = 0.04 and 0.01; SE = 1.48, 5000 > P = 0.04 and <0.01; SE = 1.34) (Fig. 3). In category > 5000 µm, SHALLOW ALTCC had significantly more pores compared to DEEP ALTCC (P = 0.01; SE = 1.34) (Fig. 3).

3.2.2. *Soil water retention*

Within the cultivated layer, reducing the intensity of cultivation increased soil water retention (SWR), where DEEP cultivation had significantly higher SWR compared to PLOUGH cultivation at the 200 – 400 mm depth, at potentials 200 and 1500 kPa (P = 0.03 and 0.03; SE = 0.02 and 0.02 respectively) (Fig. 4. B2).

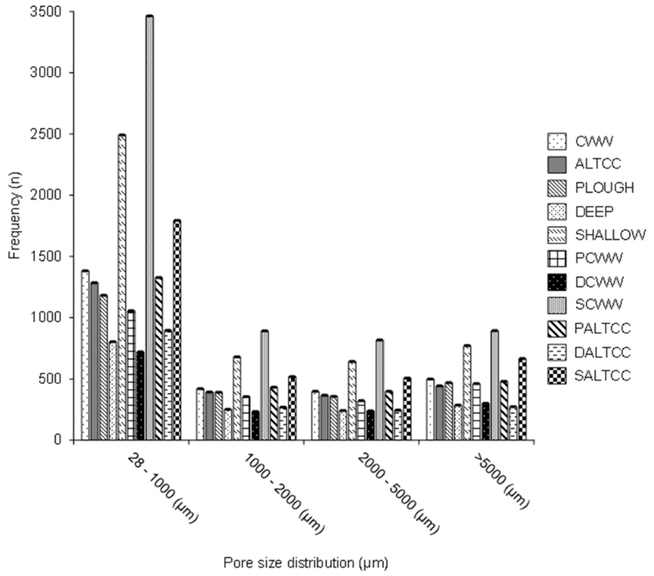


Fig. 3. Undisturbed soil core X-Ray CT pore size distribution (n) results (200 – 400 mm depth). Error bars represent standard error of the mean between treatments.

DEEP ALTCC had significantly higher SWR compared to PLOUGH ALTCC at the 200 – 400 mm depth, at potentials 200 and 1500 kPa (P = 0.03 and 0.04; SE = 0.03 and 0.03 respectively) (Fig. 4. C2). DEEP CWW had significantly higher SWR compared to DEEP ALTCC at the 600 – 800 mm depth, at potentials 0, 5 and 10 kPa (P = 0.03, 0.03 and 0.04; SE = 0.02, 0.02 and 0.02 respectively) (Fig. 4. C4). SHALLOW ALTCC had significantly higher SWR compared to DEEP ALTCC at the 600 – 800 mm depth, at potentials 5 and 10 kPa (P = 0.04 and 0.04; SE = 0.02 and 0.02 respectively) (Fig. 4. C4). DEEP ALTCC had significantly higher SWR compared to PLOUGH ALTCC at the 600 – 800 mm depth, at potential 1500 kPa (P = 0.04; SE = 0.02) (Fig. 4. C4).

3.2.3. *Root characteristics*

At depth 200 – 400 mm, treatments PLOUGH had significantly higher root diameter and lower root length across a range of treatment interactions (Fig. 5). At the same depth, SHALLOW had significantly higher root biomass compared to the higher intensity cultivation treatments and rotation did not have a significant interaction effect (Fig. 5).

At depth 600 – 800 mm, the interaction of SHALLOW and ALTCC treatments produced significantly higher root diameter and root length compared to other treatment combinations (Fig. 5). SHALLOW had significantly higher mean root diameter compared to PLOUGH and DEEP at 600 – 800 mm depth (P = 0.02 and <0.01 respectively; SE = 0.01) (Fig. 5). SHALLOW ALTCC had significantly higher mean root diameter compared to SHALLOW CWW at 600 – 800 mm depth (P = 0.05; SE = 0.01) (Fig. 5). SHALLOW ALTCC had significantly higher mean root diameter compared to PLOUGH ALTCC and DEEP ALTCC at 600 – 800 mm depth (P = 0.03 and <0.01 respectively; SE = 0.01) (Fig. 5).

ALTCC had significantly higher root length compared to CWW at 600 – 800 mm depth (P = 0.01; SE = 17.9) (Fig. 5). SHALLOW had significantly higher root length compared to PLOUGH and DEEP at 600 – 800 mm depth (P = 0.05 and 0.02 respectively; SE = 22.0) (Fig. 5). ALTCC SHALLOW had significantly higher root length compared to CWW SHALLOW and ALTCC DEEP at 600 – 800 mm depth (P = 0.02 and 0.02 respectively, SE = 31.1) (Fig. 5). SHALLOW CWW had significantly higher root biomass compared to DEEP CWW at 600 – 800 mm

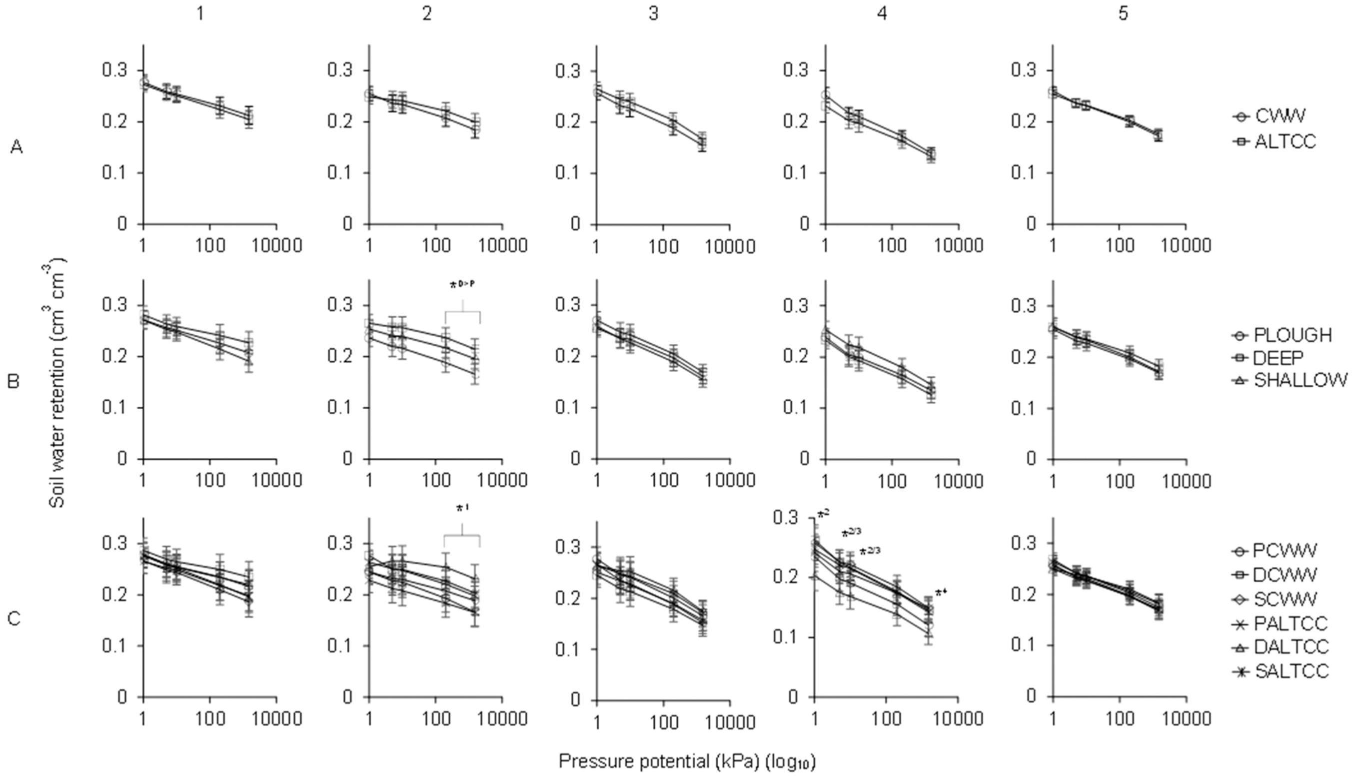


Fig. 4. Soil water retention (cm^3 cm^{-3}) over depth. 1) 0 – 200 mm 2) 200 – 400 mm 3) 400 – 600 mm 4) 600 – 800 mm 5) mean all depths; A) rotation treatments B) cultivation treatments C) rotation and cultivation treatment interaction. ALTCC – alternate cover crop, CWW – continuous winter wheat, P – plough cultivation, D – deep cultivation, S – shallow cultivation. Significant differences ($P < 0.05$) are indicated by treatments in sections A and B (e.g. *CWW>ALTCC) and by numbers in section C which correspond to the following: 1D ALTCC>P ALTCC, 2D CWW>D ALTCC, 3 S ALTCC>D ALTCC, 4D ALTCC> P ALTCC. Error bars represent standard error of the mean between treatments at each soil water potential.

depth ($P = 0.02$; $SE = 1.78$) (Fig. 5).

Rotation treatment had a limited interaction outside of treatment SHALLOW, where DEEP ALTCC had significantly higher root biomass compared to DEEP CWW at 600 – 800 mm ($P = 0.03$; $SE = 1.78$) (Fig. 5).

4. Discussion

4.1. Subsoil physical properties

Results demonstrated that rotation and cultivation treatments had significant impacts upon subsoil physical properties, and that a significant interaction between rotation and cultivation was observed. Field monitoring results showed that ALTCC rotation had lower subsoil penetration resistance and higher volumetric soil moisture that persisted later into the growing season compared to CWW. However, cultivation treatments were the strongest driver of penetration resistance, with significant differences corresponding to the working depth of cultivation treatment. Reducing cultivation intensity and increasing the diversity of rotation, have both been linked to improved topsoil physical structure and function (Blanco-Canqui et al., 2015; Chen and Weil, 2011; Tebrügge and Düring, 1999). Improved soil physical structure and function, in turn, improves water infiltration, conductivity and storage (Alaoui and Goetz, 2008; Hamza and Anderson, 2005; Menon et al., 2015), which may support why treatments ALTCC, SHALLOW and DEEP had a positive impact on subsoil volumetric soil moisture. Higher volumetric soil moisture and lower penetration resistance (depending on parameters for a given soil type) in the subsoil may better support arable crop growth (Kirkegaard et al., 2007; Whalley et al., 2008).

The soil water retention results supported volumetric soil moisture results, as PLOUGH treatment recorded lower soil water retention compared to DEEP in the subsoil (200 – 400 mm depth at 200 and 1500 kPa; 600 – 800 mm at 1500 kPa). Lower water retention at 200 and 1500 kPa water potentials indicated the subsoil under PLOUGH treatment was less able to retain water under drying field conditions at these depths. Lower subsoil water retention may limit the ability of the subsoil to support arable plant growth in drying conditions (Bengough et al., 2011; McKenzie et al., 2009).

Significant differences in water stable aggregates occurred in the 0 – 200 mm depth only. Water stable aggregate via wet sieving have been related to subsoil properties (Bartlova et al., 2015; Bronick and Lal, 2005) but has been more widely applied to soil surface properties (Amézketa, 1999; Pulido Moncada et al., 2015). Further investigation using recently published wet aggregate stability methods that focus on below surface properties (Hudek et al., 2021) may help to clarify if any benefit from rotation or cultivation approach extends to the subsoil.

4.2. Compacted pan

Treatment PLOUGH resulted in the formation of a compacted layer (250 mm) with higher PR compared to the topsoil above and the deeper subsoil below (250 – 450 mm). This compacted ‘pan layer’ was evident where the PLOUGH treatment was combined with CWW rotation but not where combined with ALTCC rotation. Cover crop root growth has been shown to alleviate soil compaction through the creation and exploration of biopores (Chen and Weil, 2010; Dexter, 1991; Pulido-Moncada et al., 2021), and these results may demonstrate that ALTCC rotation provided prevention or alleviation of the subsoil compaction that occurred where treatments PLOUGH and CWW were combined. Pore volume (%) results from X-ray CT showed that there was significantly higher porosity in the 200 – 400 mm depth for PLOUGH combined with ALTCC compared to CWW. High pore volume and lower PR is associated with better soil structure (Bengough et al., 2001) and therefore supports the PR pan

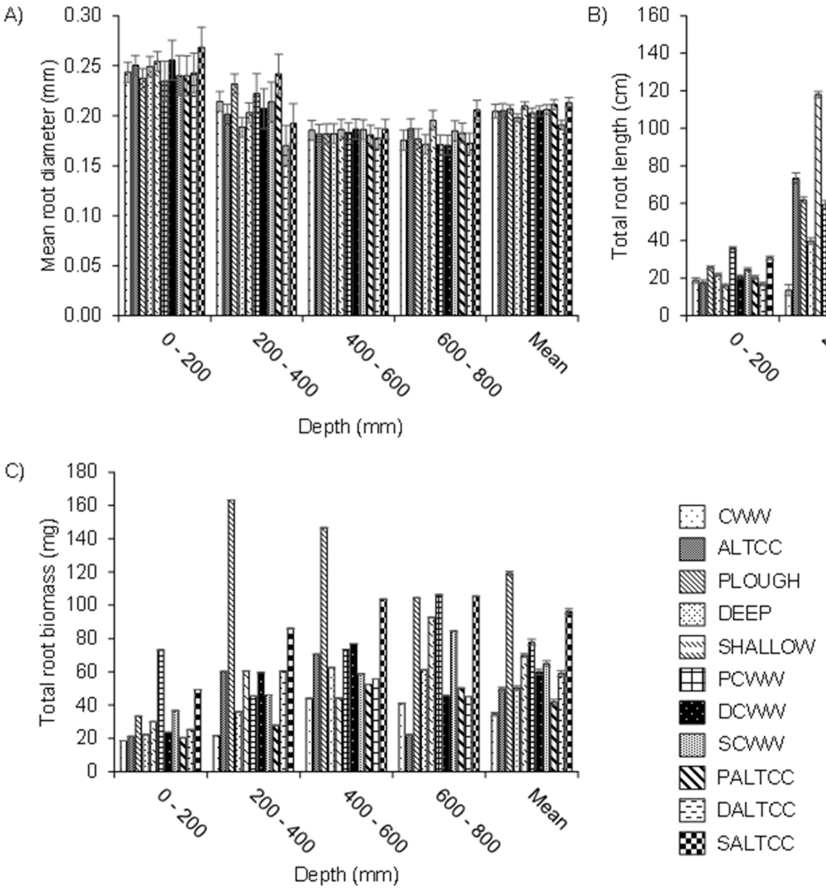


Fig. 5. Root characteristics over depth and mean of all depths ‘Mean’. A) mean root diameter (mm), B) total root length (cm), C) total root biomass (mg). Error bars represent standard error of the mean between treatments.

layer results that ALTCC rotation presented an advantage to subsoil physical properties.

There was also a significant root diameter response to PLOUGH cultivation at 200 – 400 mm depth. At this depth, PLOUGH treatment had a higher root diameter compared to both DEEP and SHALLOW cultivation, whereas deeper in the subsoil this trend was reversed with SHALLOW cultivation having higher root diameter compared to PLOUGH and DEEP treatment (600 – 800 mm). The same trend occurred where cultivation treatments were combined with ALTCC rotation but not with CWW, which at the 200 – 400 mm depth suggested parallels with the PR data. The ability to modify root diameter in response to compaction has been suggested to be an important trait in compaction alleviation (Clark et al., 2003; Hamza and Anderson, 2005). Therefore, the alleviation of the compacted pan layer observed in the PR data may be attributed to increased root diameter with ALTCC rotation (Szatanik-Kloc et al., 2019) compared to CWW.

The X-ray CT results showed that minimising cultivation (SHALLOW treatment) resulted in an improvement in soil pore volume, surface area and frequency. An additional benefit could be gained by combining SHALLOW treatment with ALTCC rotation in terms of soil pore characteristics and the frequency of large pores. Greater porosity and pore function are linked to reduced compaction and confer better subsoil conditions to support arable crop growth (de Lima et al., 2017).

4.3. Roots as rotational drivers of subsoil physical properties

The root results presented in this paper showed that reducing the depth of cultivation (SHALLOW) resulted in higher root diameter compared to DEEP cultivation, higher root length compared to PLOUGH cultivation, and higher root biomass compared to both PLOUGH and DEEP cultivation. The trends were broadly the same whether cultivation treatments were combined with CWW or ALTCC rotation, which suggested cultivation treatment was the dominant factor.

Increased rooting in the subsoil has been shown to lead to greater biopore formation through the cycling of root creation and exploration of pores, and subsequent root decay (Cresswell and Kirkegaard, 1995; Wahlström et al., 2021). This has been shown to improve soil functions in compacted layers (Han et al., 2015; Kautz, 2015; Perkons et al., 2014).

4.4. Overall discussion

Repeated cover cropping (ALTCC) resulted in some benefits to subsoil physical structure that indicated improved subsoil physical properties compared to CWW rotation. However, reducing the intensity of cultivation (SHALLOW) resulted in a stronger impact on subsoil physical structure, which suggested that overall, ALTCC rotation had a contributory role to cultivation intensity. The three alternative management approaches considered (ALTCC rotation, DEEP cultivation and SHALLOW cultivation) increased subsoil moisture compared to the controls (CWW rotation, PLOUGH cultivation). Although literature indicates that increased soil moisture may increase the risk of subsoil compaction from field operations (Arvidsson et al., 2001; Horn, 1990), the potential benefits to support crop growth in an increasingly variable UK climate may outweigh potential negatives.

The compacted pan layer observed with PLOUGH cultivation, subsequent root responses and potential alleviation, highlights the requirement to consider the whole approach to field operations when choosing alternative approaches to mechanical cultivation to improve subsoil physical properties. Despite SHALLOW treatment providing the greatest benefits to the subsoil, if inversion cultivation is a requirement, then perhaps ALTCC rotation presents a mitigation measure to maintain subsoil physical properties. Further work to define interaction relationships using a variety of soil types would be required.

Improved understanding of biological approaches to improve subsoil physical properties are likely to enable practitioners to utilise technologies in the field and increase adoption (Frelih-Larsen et al., 2018; Storr et al., 2019). Evidence presented here suggested repeated cover cropping and reducing the intensity of cultivation over the long-term have potential to reduce the need and negative impacts of mechanical cultivation.

5. Conclusions

Degradation of subsoil physical properties in arable soils reduces the efficiency of arable crop production and has the potential to negatively impact wider ecosystem services. Repeated cover cropping (ALTCC) demonstrated positive rotational benefits to subsoil physical structure compared to the control (CWW). Reducing the intensity of cultivation through cultivating at shallower depths (SHALLOW) or using non-inversion (DEEP) had a generally positive impact on subsoil properties and strongly influenced any benefit gained from ALTCC rotation. The combination of ALTCC rotation and SHALLOW cultivation produced the greatest long-term benefits to subsoil physical properties.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

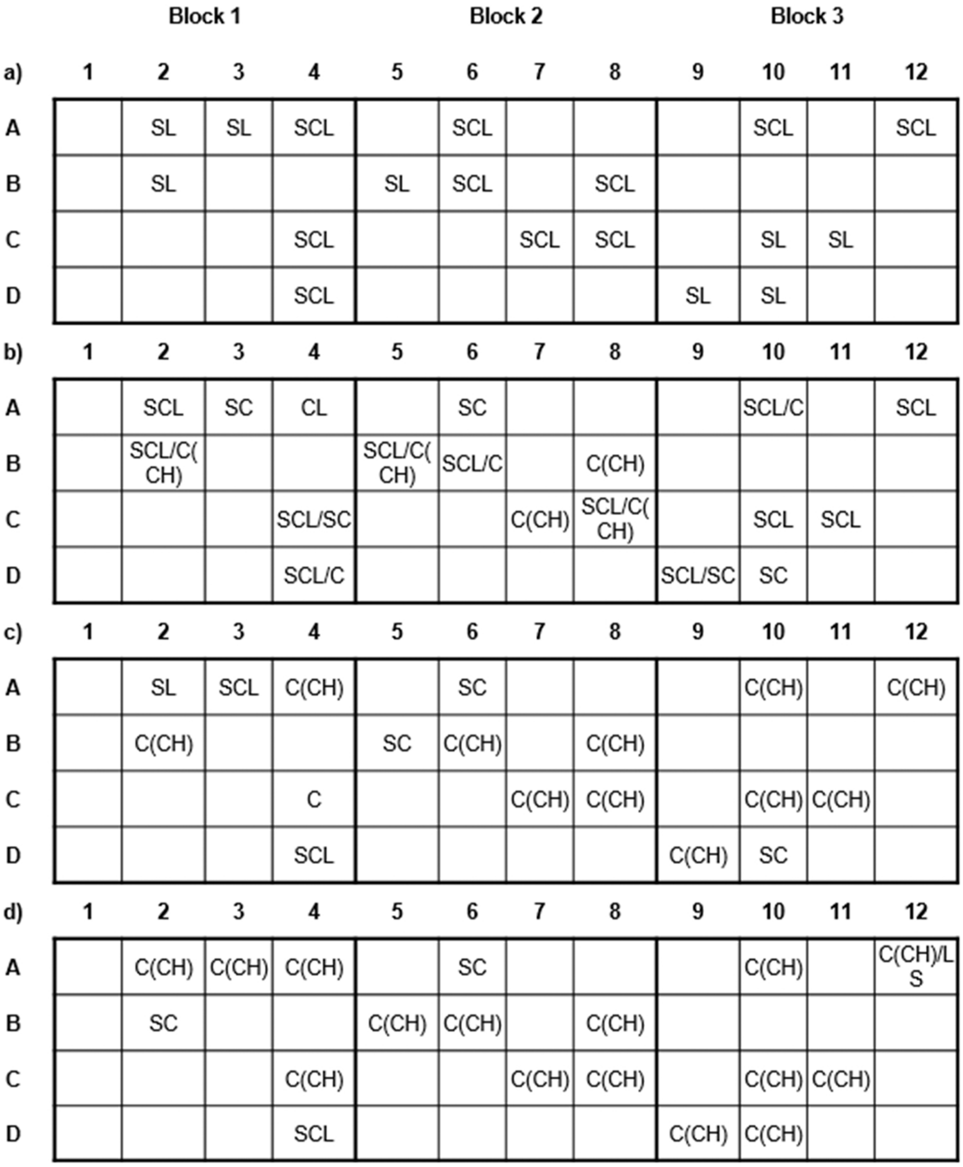
Data Availability

Data will be made available on request.

Acknowledgements

This research was supported by The Felix Thornley Cobbold Trust, The Chadacre Trust, The Morley Agricultural Foundation and NIAB. The authors wish to acknowledge the valuable contributions from technical staff at Cranfield University, NIAB and the Hounsfield Facility at the University of Nottingham. We thank UK Agri-Tech Centre, Crop Health and Protection (CHAP), funded by Innovate UK, for the use of their facilities to conduct part of this research.

Appendix A



	Block 1				Block 2				Block 3			
a)	1	2	3	4	5	6	7	8	9	10	11	12
A		SL	SL	SCL		SCL				SCL		SCL
B		SL			SL	SCL		SCL				
C				SCL			SCL	SCL		SL	SL	
D				SCL					SL	SL		

b)	1	2	3	4	5	6	7	8	9	10	11	12
A		SCL	SC	CL		SC				SCL/C		SCL
B		SCL/C(CH)			SCL/C(CH)	SCL/C		C(CH)				
C				SCL/SC			C(CH)	SCL/C(CH)		SCL	SCL	
D				SCL/C					SCL/SC	SC		

c)	1	2	3	4	5	6	7	8	9	10	11	12
A		SL	SCL	C(CH)		SC				C(CH)		C(CH)
B		C(CH)			SC	C(CH)		C(CH)				
C				C			C(CH)	C(CH)		C(CH)	C(CH)	
D				SCL					C(CH)	SC		

d)	1	2	3	4	5	6	7	8	9	10	11	12
A		C(CH)	C(CH)	C(CH)		SC				C(CH)		C(CH)/LS
B		SC			C(CH)	C(CH)		C(CH)				
C				C(CH)			C(CH)	C(CH)		C(CH)	C(CH)	
D				SCL					C(CH)	C(CH)		

Fig. A1. NIAB STAR experiment soil texture over depth a) 0 – 200 mm, b) 200 – 400 mm, c) 400 – 600 mm, d) 600 – 800 mm (SL - sandy loam, SCL - sandy clay loam, SC - sandy clay, C - clay, CL – clay loam, LS - loamy sand, CH - chalk) (blank spaces represent experimental plots not considered during this experiment).

Appendix B

Table B.1
Herbal ley plot cultivation treatments.

Treatment	Cultivation Method	Cultivation Date	Drilling Method	Drilling Date
Plough	Sumo Trio ~10 cm (legs off)	31/08/2018	Weaving tine drill	
	Power Harrow	01/09/2018	Cambridge Roll	03/09/2018
Managed	Sumo Trio ~10 cm (legs off)	31/08/2018	Weaving tine drill	
	Power Harrow	01/09/2018	Cambridge Roll	03/09/2018
Shallow	Sumo Trio ~10 cm (legs off)	31/08/2018	Weaving tine drill	
	Power Harrow	01/09/2018	Cambridge Roll	03/09/2018
Deep	Sumo Trio ~10 cm (legs off)	31/08/2018	Weaving tine drill	
	Power Harrow	01/09/2018	Cambridge Roll	03/09/2018

Table B.2
Herbal ley plots herbicide treatment.

Input type	Product	Product rate (l ha^{-1})	Date
Herbicide	Glyphosate 360	3.0	30/08/2018

Table B.3
Herbal ley treatment species mixture.

Group	Species (variety)	%	kg/ha
Grasses	*Festulolium* (Tified FEDORO)	11.5	3.7
	Dactylis glomerata (DONATA Cocksfoot)	11.5	3.7
	Lolium perenne (NIFTY Perennial Ryegrass)	9.2	3.0
	Phleum pratense (Winnetou Timothy)	4.6	1.5
	Festuca pratensis (PARDUS Meadow fescue)	3.9	1.2
	Festuca arundinacea (KORA Tall fescue)	3.9	1.2
Legumes	*Trifolium pratense* (GLOBAL Red clover)	5.4	1.7
	Trifolium repens (ABERDAI White clover)	1.5	0.5
	Trifolium repens (ABERHERALD White clover)	2.3	0.7
	Trifolium hybridum (LOMIAI Alsike clover)	1.5	0.5
	Lotus corniculatus (LEO Birdsfoot trefoil)	1.5	0.5
	Medicago sativa (Luzelle Lucerne)	2.3	0.7
	Onobrychis viciifolia (Sainfoin)	19.2	6.2
	Melilotus officinalis (Sweet clover)	7.7	2.5
Herb	*Cichorium intybus* (PUNA II Chicory)	4.6	1.5
	Plantago lanceolata (ENDURANCE Ribgrass)	1.5	0.5
	Sanguisorba minor (Burnet)	5.4	1.7
	Achillea millefolium (Yarrow)	0.8	0.2
	Petroselenium crispum (Sheeps Parsley)	1.5	0.5
Total	19	100	32

Appendix C

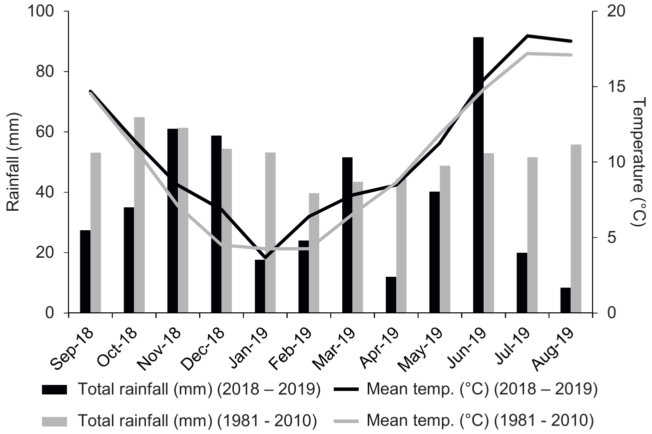


Fig. C1. Weather station data at NIAB STAR experiment site (September 2018 to August 2019)(Met Office (2020) The HADUK-Grid dataset. Met Office, UK).

Appendix D

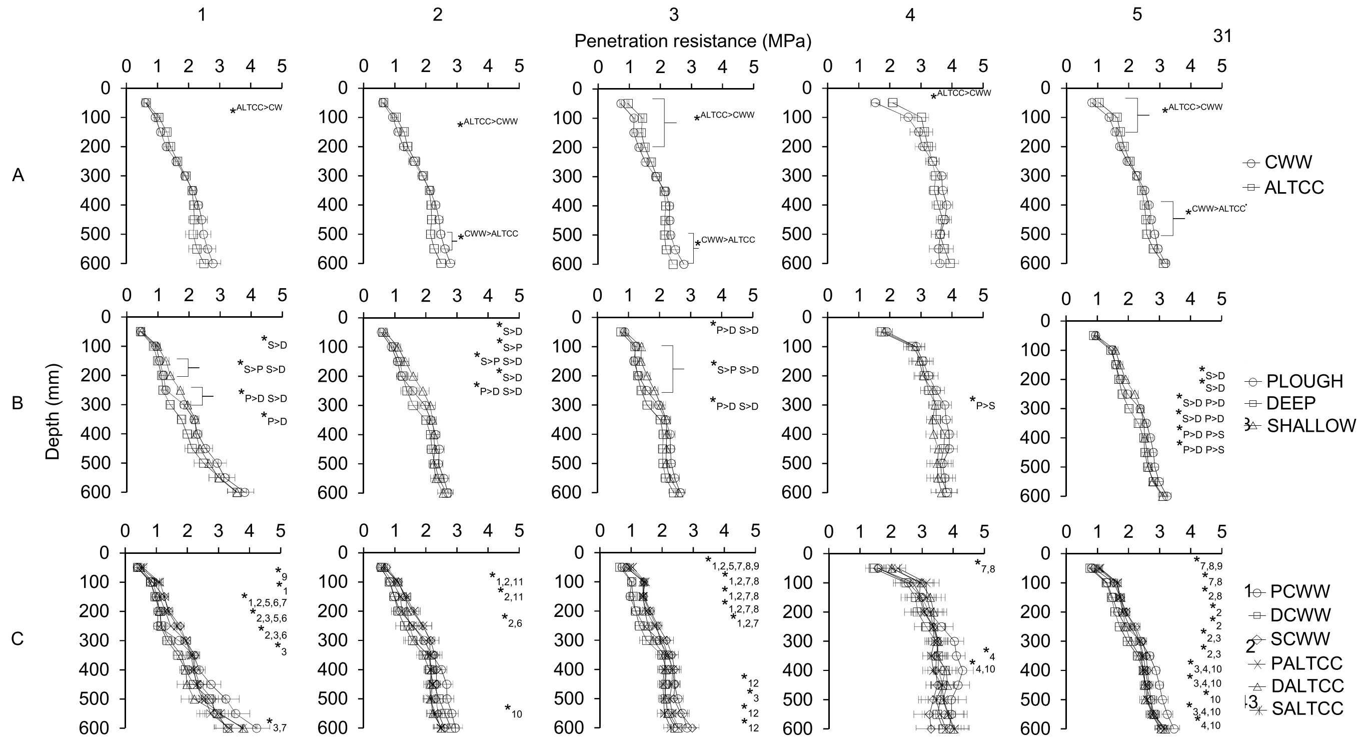


Fig. D1. Penetration resistance (MPa) over depth. 1) Nov 2018 2) Jan 2019 3) Mar 2019 4) May 2019 5) mean all collection dates; A) mean rotation treatments B) mean cultivation treatments C) rotation and cultivation treatment interaction. ALTCC – alternate cover crop, CWW – continuous winter wheat, P – plough cultivation, D – deep cultivation, S – shallow cultivation. Significant differences ($P < 0.05$) are indicated by treatments in sections A and B (e.g. *CWW>ALTCC) and by numbers in section C which correspond to the following: 1 S CWW>P CWW, 2 S CWW>D CWW, 3 P CWW>D CWW, 4 P CWW>S CWW, 5 P ALTCC>D ALTCC, 6 S ALTCC>D ALTCC, 7 P ALTCC>P CWW, 8D ALTCC>D CWW, 9 S ALTCC>S CWW, 10 P CWW>P ALTCC, 11D CWW>D ALTCC, 12 S CWW>S ALTCC. Error bars represent standard error of the mean between treatments at each depth category.

Appendix E

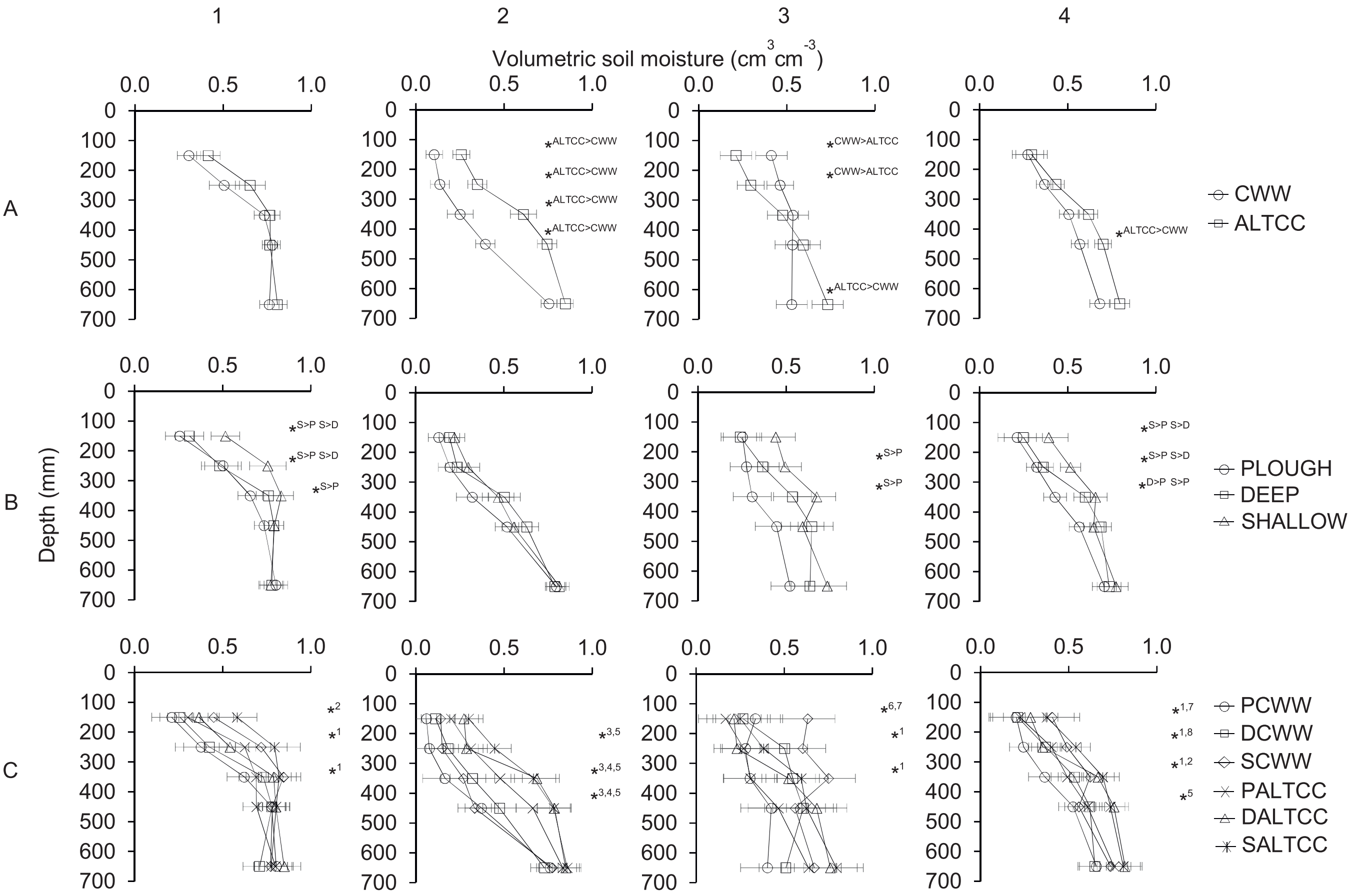


Fig. E1. Volumetric soil moisture (cm3 cm-3) over depth. 1) Mar 2019 2) May 2019 3) Aug 2019 4) mean all collection dates; A) rotation treatments B) cultivation treatments C) rotation and cultivation treatment interaction. ALTCC – alternate cover crop, CWW – continuous winter wheat, P – plough cultivation, D – deep cultivation, S – shallow cultivation. Significant differences ($P < 0.05$) are indicated by treatments in sections A and B (e.g. *CWW>ALTCC) and by numbers in section C which correspond to the following: 1 S CWW>P CWW, 2 S ALTCC>P ALTCC, 3 P ALTCC>P CWW, 4D ALTCC>D CWW, 5 S ALTCC>S CWW, 6 S CWW>S ALTCC, 7 S CWW>D CWW, 8SALTCC>DALTCC. Error bars represent standard error of the mean between treatments at each depth category.

References

Alakukku, L., Weisskopf, P., Chamen, W.C.T., Tijink, F.G.J., Van Der Linden, J.P., Pires, S., Sommer, C., Spoor, G., 2003. Prevention strategies for field traffic-induced subsoil compaction: a review Part 1. Machine/soil interactions. Soil Tillage Res. 73, 145–160. https://doi.org/10.1016/S0167-1987(03)00107-7.

Alaoui, A., Goetz, B., 2008. Dye tracer and infiltration experiments to investigate macropore flow. Geoderma 144 (1–2), 279–286. https://doi.org/10.1016/j.geoderma.2007.11.020.

Amézketa, E., 1999. Soil aggregate stability: a review. J. Sustain. Agric. 14 (2–3), 83–151. https://doi.org/10.1300/J064v14n02_08.

Arvidsson, J., 2001. Subsoil compaction caused by heavy sugarbeet harvesters in southern Sweden. Soil Tillage Res. 60 (1–2), 67–78. https://doi.org/10.1016/S0167-1987(01)00169-6.

Arvidsson, J., Trautner, A., Van Den Akker, J.J.H., Schjønning, P., 2001. Subsoil compaction caused by heavy sugarbeet harvesters in southern Sweden II. Soil displacement during wheeling and model computations of compaction. Soil Tillage Res. 60 (1–2), 79–89. https://doi.org/10.1016/S0167-1987(01)00168-4.

Atkinson, J.A., Hawkesford, M.J., Whalley, W.R., Zhou, H., Mooney, S.J., 2020. Soil strength influences wheat root interactions with soil macropores. Plant, Cell Environ. 43 (1), 235–245. https://doi.org/10.1111/pce.13659.

Bartlova, J., Badalikova, B., Pospisilova, L., Pokorny, E., Sarapatka, B., 2015. Water stability of soil aggregates in different systems of tillage, soil and water research, 10 (3), 147–154. https://doi.org/10.17221/132%2F2014-SWR.

Bengough, A.G., Campbell, D., O'Sullivan, M., 2001. Penetrometer techniques in relation to soil compaction and root growth. In: Smith, K., Mullins, C. (Eds.), Soil and Environmental Analysis. Taylor & Fransis Group, pp. 377–403.

Bengough, A.G., McKenzie, B.M., Hallett, P.D., Valentine, T.A., 2011. Root elongation, water stress, and mechanical impedance: a review of limiting stresses and beneficial root tip traits. J. Exp. Bot. 59–68. https://doi.org/10.1093/jxb/erq350.

Berisso, F.E., Schjønning, P., Keller, T., Lamandé, M., Etana, A., de Jonge, L.W., Iversen, B.V., Arvidsson, J., Forkman, J., 2012. Persistent effects of subsoil compaction on pore size distribution and gas transport in a loamy soil, Soil and Tillage Research, 122, 42–51. https://doi.org/10.1016/j.still.2012.02.005.

Blanco-Canqui, H., Shaver, T.M., Lindquist, J.L., Shapiro, C.A., Elmore, R.W., Francis, C. A., Hergert, G.W., 2015. Cover crops and ecosystem services: insights from studies in temperate soils. Agron. J. 107 (6), 2449–2474. https://doi.org/10.2134/agronj15.0086.

Bronick, C.J., Lal, R., 2005. Soil structure and management: a review. Geoderma 124 (1–2), 3–22. https://doi.org/10.1016/j.geoderma.2004.03.005.

Brus, D.J., van den Akker, J.J.H., 2018. How serious a problem is subsoil compaction in the Netherlands? A survey based on probability sampling. SOIL 4 (1), 37–45. https://doi.org/10.5194/soil-4-37-2018.

BSI, 1994. BS 3882:1994 specification for topsoil. BSI Stand. Ltd.: Lond.

BSI, 2000. BS EN 13039:2020 determination of the organic matter content and ash. BSI Stand. Ltd.: Lond.

BSI, 2013. BS 8601:2013 specification for subsoil and requirements for use. BSI Stand. Ltd.: Lond.

BSI (2019) BS EN ISO 11274:2019 Soil quality - Determination of the water-retention characteristics - Laboratory methods. BSI Standards Limited: London.

Burr-Hersey, J.E., Mooney, S.J., Bengough, A.G., Mairhofer, S., Ritz, K., 2017. Developmental morphology of cover crop species exhibit contrasting behaviour to changes in soil bulk density, revealed by X-ray computed tomography. PLOS ONE 12 (7), e0181872. https://doi.org/10.1371/journal.pone.0181872.

Carof, M., De Tourdonnet, S., Coquet, Y., Hallaire, V., Roger-Estrade, J., 2007. Hydraulic conductivity and porosity under conventional and no-tillage and the effect of three species of cover crop in northern France. Soil Use Manag. 23 (3), 230–237. https://doi.org/10.1111/j.1475-2743.2007.00085.x.

Chamen, W.C., Alakukku, L., Pires, S., Sommer, C., Spoor, G., Tijink, F., Weisskopf, P., 2003. Prevention strategies for field traffic-induced subsoil compaction: A review Part 2. Equipment and field practices. Soil Tillage Res. 73, 161–174. https://doi.org/10.1016/S0167-1987(03)00108-9.

Chen, G., Weil, R.R., 2010. Penetration of cover crop roots through compacted soils. Plant Soil 331 (1), 31–43. https://doi.org/10.1007/s11104-009-0223-7.

Chen, G., Weil, R.R., 2011. Root growth and yield of maize as affected by soil compaction and cover crops. Soil Tillage Res. 117, 17–27. https://doi.org/10.1016/j.still.2011.08.001.

Clark, L.J., Whalley, W.R., Barraclough, P.B., 2003. How do roots penetrate strong soil? Plant Soil 255, 93–104. https://doi.org/10.1023/A:1026140122848.

Cresswell, H., Kirkegaard, J., 1995. Subsoil amelioration by plant-roots - the process and the evidence. Aust. J. Soil Res. 33 (2), 221–239. https://doi.org/10.1071/SR9950221.

Dexter, A.R., 1991. Amelioration of soil by natural processes. Soil Tillage Res. 20 (1), 87–100. https://doi.org/10.1016/0167-1987(91)90127-J.

do Rosario G., Oliveira M., van Noordwijk M., Gaze S.R., Brouwer G., Bona S., Mosca G., Hairiah K. 2000. Auger sampling, ingrowth cores and pinboard methods. In: Smit A. L., Bengough A.G., Engels C., Noordwijk M., Pellerin S., Geijn S.C., (eds), Root Methods: A Handbook. Berlin: SpringerVerlag, 175–210.

Doube, M., Klosowski, M.M., Arganda-Carreras, I., Cordelières, F.P., Dougherty, R.P., Jackson, J.S., Schmid, B., Hutchinson, J.R., Shefelbine, S.J., 2010. BoneJ: Free and extensible bone image analysis in ImageJ. Bone 47 (6), 1076–1079. https://doi.org/10.1016/j.bone.2010.08.023.

Etana, A., Håkansson, I., 1994. Swedish experiments on the persistence of subsoil compaction caused by vehicles with high axle load. Soil Tillage Res. 29 (2–3), 167–172. https://doi.org/10.1016/0167-1987(94)90053-1.

Falconer, R.E., Houston, A.N., Otten, W., Baveye, P.C., 2012. Emergent behaviour of soil fungal dynamics. Soil Sci. 177 (2), 111–119. https://doi.org/10.1097/SS.0b013e318241133a.

Frelih-Larsen, A., Hinzmann, M., Ittner, S., 2018. The "invisible" subsoil: an exploratory view of societal acceptance of subsoil management in Germany. Sustainability 10 (9), 3006. https://doi.org/10.3390/su10093006.

Håkansson, I., 1994. Subsoil compaction caused by heavy vehicles-a long-term threat to soil productivity. Soil Tillage Res. 29 (2–3), 105–110.

Håkansson, I., Reeder, R.C., 1994. Subsoil compaction by vehicles with high axle load—extent, persistence and crop response. Soil Tillage Res. 29 (2–3), 277–304. https://doi.org/10.1016/0167-1987(94)90065-5.

Hamza, M.A., Anderson, W.K., 2005. Soil compaction in cropping systems: a review of the nature, causes and possible solutions. Soil Tillage Res. 82 (2), 121–145. https://doi.org/10.1016/j.still.2004.08.009.

Han, E., Kautz, T., Perkons, U., Uteau, D., Peth, S., Huang, N., Horn, R., Köpke, U., 2015. Root growth dynamics inside and outside of soil biopores as affected by crop sequence determined with the profile wall method. Biol. Fertil. Soils 51 (7), 847–856. https://doi.org/10.1007/s00374-015-1032-1.

Hernanz, J., Sanchez-Giron, V., 2000. Compaction effects due to field traffic on soil properties and the response of different crops in three tillage systems. In: Horn, R., Van den Akker, J.J.H., Arvidsson, J. (Eds.), Subsoil Compaction—Distribution, Processes and Consequences, Advances in Geoecology, 32, pp. 269–277.

Hodge, C.A.H., Burton, R.G.O., Corbett, W.M., Evans, R., Seale, R.S., 1984. Soils and their use in Eastern England. Soil Survey of England and Wales Bulletin No. 13. Soil Survey of England and Wales 1984, Harpenden.

Horn, R., 1990. Structure effects on strength and stress distribution in arable soils. ASAE International Summer Meeting. Columbus, Ohio 24-27th June 1990. ASAE,, Ohio, pp. 8–20.

Houston, A.N., Schmidt, S., Tarquis, A.M., Otten, W., Baveye, P.C., Hapca, S.M., 2013. Effect of scanning and image reconstruction settings in X-ray computed microtomography on quality and segmentation of 3D soil images. Geoderma 207–208, 154–165. https://doi.org/10.1016/j.geoderma.2013.05.017.

Houston, A.N., Otten, W., Falconer, R., Monga, O., Baveye, P.C., Hapca, S.M., 2017. Quantification of the pore size distribution of soils: Assessment of existing software using tomographic and synthetic 3D images. Geoderma 299, 73–82. https://doi.org/10.1016/j.geoderma.2017.03.025.

Hudek, C., Putinica, C., Otten, W., De Baets, S., 2021. Functional root trait classification of cover crops to improve soil physical properties. Eur. J. Soil Sci. 73 (1), e13147 https://doi.org/10.1111/ejss.13147.

Jones, R.J.A., Spoor, G., Thomasson, A.J., 2003. Vulnerability of subsoils in Europe to compaction: a preliminary analysis. Soil Tillage Res. 73, 131–143. https://doi.org/10.1016/S0167-1987(03)00106-5.

Kautz, T., 2015. Research on subsoil biopores and their functions in organically managed soils: a review. Renew. Agric. Food Syst. 30 (4), 318–327 https://doi:10.1017/S1742170513000549.

Keller, T., Sandin, M., Colombi, T., Horn, R., Or, D., 2019. Historical increase in agricultural machinery weights enhanced soil stress levels and adversely affected soil functioning. Soil Tillage Res. 194, 104293 https://doi.org/10.1016/j.still.2019.104293.

Kemper, W.D., Rosenau, R.C., 1986. Aggregate stability and size distribution. In: Klute, A. (Ed.), Methods of Soil Analysis Part 1, Physical and Mineralogical Methods. Agronomy Monograph Nº 9, second edition. American Society of Agronomy, Inc., Madison, WI.

Kirkegaard, J.A., Lilley, J., Howe, G., Graham, J., 2007. Impact of subsoil water use on wheat yield. Aust. J. Agric. Res. 58 (4), 303–315. https://doi.org/10.1071/AR06285.

Landl, M., Schnepf, A., Uteau, D., Peth, S., Athmann, M., Kautz, T., Perkons, U., Vereecken, H., Vanderborght, J., 2019. Modelling the Impact of Biopores on Root Growth and Root Water Uptake. Vadose Zone J. 18 (1), 1–20. https://doi.org/10.2136/vzj2018.11.0196.

de Lima, R., da Silva, Á.P., Giarola, N., da Silva, A., Rolim, M., 2017. Changes in soil compaction indicators in response to agricultural field traffic. Biosyst. Eng. 162, 1–10. https://doi.org/10.1016/j.biosystemseng.2017.07.002.

Lipiec, J., Hatano, R., 2003. Quantification of compaction effects on soil physical properties and crop growth. Geoderma 116 (1–2), 107–136. https://doi.org/10.1016/S0016-7061(03)00097-1.

Lipiec, J., Arvidsson, J., Murer, E., 2003. Review of modelling crop growth, movement of water and chemicals in relation to topsoil and subsoil compaction. Soil Tillage Res. 73 (1–2), 15–29. https://doi.org/10.1016/S0167-1987(03)00096-5.

Materechera, S.A., Alston, A.M., Kirby, J.M., Dexter, A.R., 1992. Influence of root diameter on the penetration of seminal roots into a compacted subsoil. Plant Soil 144 (2), 297–303. https://doi.org/10.1007/BF00012888.

McKenzie, B.M., Bengough, A.G., Hallett, P.D., Thomas, W.T.B., Forster, B., McNicol, J. W., 2009. Deep rooting and drought screening of cereal crops: a novel field-based method and its application. Field Crops Res. 112 (2–3), 165–171. https://doi.org/10.1016/j.fcr.2009.02.012.

Menon, M., Jia, X., Lair, G.J., Faraj, P.H., Blaud, A., 2015. Analysing the impact of compaction of soil aggregates using X-ray microtomography and water flow simulations. Soil Tillage Res. 150, 147–157. https://doi.org/10.1016/j.still.2015.02.004.

Olesen, J., Munkholm, L.J., 2007. Subsoil loosening in a crop rotation for organic farming eliminated plough pan with mixed effects on crop yield. Soil Tillage Res. 94, 376–385. https://doi.org/10.1016/j.still.2006.08.015.

Perkons, U., Kautz, T., Uteau, D., Peth, S., Geier, V., Thomas, K., Lütke Holz, K., Athmann, M., Pude, R., Köpke, U., 2014. Root-length densities of various annual crops following crops with contrasting root systems. Soil Tillage Res. 137, 50–57. https://doi.org/10.1016/j.still.2013.11.005.

Poodt, M.P., Koolen, A.J., Van Der Linden, J.P., 2003. FEM analysis of subsoil reaction on heavy wheel loads with emphasis on soil preconsolidation stress and cohesion. Soil Tillage Res. 73 (1–2), 67–76. https://doi.org/10.1016/S0167-1987(03)00100-4.

Pulido Moncada, M., Gabriels, D., Cornelis, W., Lobo, D., 2015. Comparing aggregate stability tests for soil physical quality indicators. Land Degrad. Dev. 26 (8), 843–852. https://doi.org/10.1002/ldr.2225.

Pulido-Moncada, M., Katuwal, S., Ren, L., Cornelis, W., Munkholm, L., 2020. Impact of potential bio-subsoilers on pore network of a severely compacted subsoil. Geoderma 363, 114154. https://doi.org/10.1016/j.geoderma.2019.114154.

Pulido-Moncada, M., Katuwal, S., Kristensen, J.B., Munkholm, L.J., 2021. Effects of bio-subsoilers on subsoil pore-system functionality: case study with intact soil columns. Geoderma 385, 114897. https://doi.org/10.1016/j.geoderma.2020.114897.

Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H.-J., 2018. Soil structure as an indicator of soil functions: a review. Geoderma 314, 122–137. https://doi.org/10.1016/j.geoderma.2017.11.009.

Rickson, R.J., Deeks, L.K., Graves, A., Harris, J.A.H., Kibblewhite, M.G., Sakrabani, R., 2015. Input constraints to food production: the impact of soil degradation. Food Secur. 7 (2), 351–364. https://doi.org/10.1007/s12571-015-0437-x.

Schaffer, B., Stauber, M., Muller, R., Schulin, R., 2007. Changes in the macro-pore structure of restored soil caused by compaction beneath heavy agricultural machinery: a morphometric study. Eur. J. Soil Sci. 58, 1062–1073. https://doi.org/10.1111/j.1365-2389.2007.00886.x.

Schaffer, B., Mueller, T., Stauber, M., Muller, R., Keller, M., Schulin, R., 2008. Soil and macro-pores under uniaxial compression. II. Morphometric analysis of macro-pore stability in undisturbed and repacked soil. Geoderma 146, 175–182. https://doi.org/10.1016/j.geoderma.2008.05.020.

Schindelin, J., Arganda-Carreras, I., Frise, E., Kaynig, V., Longair, M., Pietzsch, T., Preibisch, S., Rueden, C., Saalfeld, S., Schmid, B., Tinevez, J.Y., White, D.J., Hartenstein, V., Eliceiri, K., Tomancak, P., Cardona, A., 2012. Fiji: an open-source platform for biological-image analysis. Nat. Methods 9 (7), 676–682. https://doi.org/10.1038/nmeth.2019.

Schneider, F., Don, A., 2019a. Root-restricting layers in German agricultural soils. Part I: extent and cause. Plant Soil 442 (1–2), 433–451. https://doi.org/10.1007/s11104-019-04185-9.

Schneider, F., Don, A., 2019b. Root-restricting layers in German agricultural soils. Part II: adaptation and melioration strategies. Plant Soil 442 (1–2), 419–432. https://doi.org/10.1007/s11104-019-04186-8.

Schonning, P., Thorsoe, M., 2019. Soil compaction – drivers, pressures, state, impacts and responses. DCA Report No 155. Aarhus University, Denmark.

Schonning, P., Lamande, M., Thorsoe, M., Frelih-Larsen, A., 2018. Policy brief: subsoil compaction - a threat to sustainable food production and soil ecosystem services. RECARE, Denmark.

Sommer, C., 2000. Management of the arable layer to avoid subsoil compaction. Proceedings of the Third Workshop of the Concerted Action on Subsoil Compaction. Uppsala, Sweden June 14 – 16th 2000. Department of Soil Sciences, Swedish University of Agricultural Sciences, Uppsala, Sweden, pp. 173–177.

Spoor, G., Tijink, F.G.J., Weisskopf, P., 2003. Subsoil compaction: risk, avoidance, identification and alleviation. Soil Tillage Res. 73, 175–182. https://doi.org/10.1016/S0167-1987(03)00109-0.

Stobart, R., Morris, N.L., 2011. Sustainability Trial in Arable Rotations (STAR project): a long term farming systems study looking at rotation and cultivation practice. Asp. Appl. Biol. 113, 67–73.

Storr, T., Simmons, R.W., Hannam, J.A., 2019. A UK survey of the use and management of cover crops. Ann. Appl. Biol. 174 (2), 12488. https://doi.org/10.1111/aab.12488.

Szatanik-Kloc, A., Horn, R., Lipiec, J., Siczek, A., Boguta, P., 2019. Initial growth and root surface properties of dicotyledonous plants in structurally intact field soil and compacted headland soil. Soil Tillage Res. 195, 104387 https://doi.org/10.1016/j.still.2019.104387.

Tebrügge, F., Düring, R.A., 1999. Reducing tillage intensity - a review of results from a long-term study in Germany. Soil Tillage Res. 53 (1), 15–28. https://doi.org/10.1016/S0167-1987(99)00073-2.

Trautner, A., Van Den Akker, J.J.H., Fleige, H., Arvidsson, J., Horn, R., 2003. A subsoil compaction database: Its development, structure and content. Soil Tillage Res. 73, 9–13. https://doi.org/10.1016/S0167-1987(03)00095-3.

Uteau, D., Pagenkemper, S., Peth, S., Horn, R., 2013. Root and time dependent soil structure formation and its influence on gas transport in the subsoil. Soil Tillage Res. 132, 69–76. https://doi.org/10.1016/j.still.2013.05.001.

Vogel, H.J., Weller, U., Schlüter, S., 2010. Quantification of soil structure based on Minkowski functions. Comput. Geosci. 36 (10), 1236–1245. https://doi.org/10.1016/j.cageo.2010.03.007.

Wahlström, E.M., Kristensen, H.L., Thomsen, I., Labouriau, R., Pulido-Moncada, M., Neilsen, J., Munkholm, L.J., 2021. Subsoil compaction effect on spatio-temporal root growth, reuse of biopores and crop yield of spring barley. Eur. J. Agron. 123, 126225 https://doi.org/10.1016/j.eja.2020.126225.

Whalley, W.R., Watts, C.W., Gregory, A.S., Mooney, S.J., Clark, L.J., Whitmore, A.P., 2008. The effect of soil strength on the yield of wheat. Plant Soil 306, 237–247. https://doi.org/10.1007/s11104-008-9577-5.

Williams, S.M., Weil, R.R., 2004. Crop cover root channels may alleviate soil compaction effects on soybean crop. Soil Sci. Soc. Am. J. 68 (4), 1403. https://doi.org/10.2136/sssaj2004.1403.