

DR. MICHAEL L GIANNITSOPOULOS (Orcid ID : 0000-0001-8952-7244)

Article type : Research Paper

**Effects of conservation tillage drills on soil quality indicators in a wheat-oilseed rape rotation:
organic carbon, earthworms and water stable aggregates**

Michail L. Giannitsopoulos¹, Paul J. Burgess¹ and Jane Rickson¹

¹Cranfield University, Cranfield, Bedfordshire, MK43 0AL, UK

Corresponding Author: Michail Giannitsopoulos Email address: m.giannitsopoulos@cranfield.ac.uk

Running title: Conservation tillage

Abstract

The effects of five conservation tillage drills with crop residue levels covering between 17% and 79% of the soil, and tillage depths ranging from 25 mm to 200 mm, were examined over three years. The tillage systems ranged from a relatively disruptive Farm System to a Low Disruption system, with three intermediate treatments labelled Sumo DTS, Claydon, and Mzuri. The study involved field sites on a clay or clay loam soil, where winter wheat and oilseed rape were grown in rotation. In the clay field, the Mzuri and Low Disruption treatments, which produced the highest residue coverage, showed the greatest increase in surface total soil organic carbon (1.1 and 0.48 Mg C ha⁻¹ respectively) between year 1 and 3. The least disruptive tillage system also resulted in the highest density of earthworms (181-228 m⁻²), and the most disruptive system produced the lowest densities (75-98 m⁻²). In the third year, the least disruptive system also showed a higher proportion of water

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process, which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1111/sum.12536

This article is protected by copyright. All rights reserved.

Accepted Article

stable aggregates (29.8%) than the other treatments (22.7-25.3%). Linear regressions showed positive relationships of both soil organic carbon and earthworm density with surface residue cover, and of the proportion of water stable aggregates with soil organic carbon.

Key words: Cultivation, crop residue, organic carbon, aggregates

1. Introduction

Soil quality is a product of inherent (parent material, climate and topography) and anthropogenic (tillage and crop rotation) interactions (Karlen et al. 1997). It reflects the capacity of a soil to function within an ecosystem to sustain biological productivity, maintain environmental quality, and promote plant and animal health (Doran et al. 2002; Karlen et al. 2008). Other potential functions of a soil include a source of raw material, a physical basis for human activities, and a storage site of genetic material, and elements of geogenic and cultural heritage (Blum 2005). An increasingly recognised function of soils is the storage of carbon to reduce the atmospheric increase in carbon dioxide and thereby climate change (CEC 2006). In addition, increasing soil organic carbon can help prevent soil quality degradation and the loss of fertile land (Lal 2004; Brandão et al. 2011). For these reasons, soil organic carbon is a useful indicator when comparing the environmental impacts of different land management practices (Brandão et al. 2011). Soil biology is also a useful indicator of soil quality and high levels of soil biota can reduce soil degradation and desertification (Lal 2015). Soil biota, which occurs at micro-, meso-, and macro-levels, perform critical roles in the decomposition of biomass, the cycling of nutrients, and the suppression of diseases. Soil quality is also dependent on soil structure and aggregate stability (Nimmo 2004; Muñoz-Rojas 2016; Rabot et al. 2018), which in turn can affect root growth. Because of their direct relation to cohesive forces, aggregate size and stability are also important to the understanding of soil erosion and surface sealing (Nimmo 2004).

A key management decision in the production of annual arable crops is the type and intensity of tillage. Whereas inversion tillage buries most of the crop residue and leaves the soil surface almost totally bare, conservation tillage retains most of the harvest residues from the previous crop on the soil surface (Rasnake, 1983; OECD, 2001). CTIC (2002) and Soane et al. (2012) have also specified that conservation tillage should result in the crop residue covering 30 percent or more of the soil surface.

Chatskikh et al. (2008) reported that soil tillage intensity can affect both crop growth and soil carbon (C) and nitrogen (N) turnover and balances, including emissions of greenhouse gases (GHG) such as CO₂ and N₂O. Agronomic practices such as tillage, residue management and crop rotation determine the quantity of carbon (C) retained in the soil (Blanco-Canqui and Lal 2007). In addition, the amount of residue left on the surface is determined by the number of passes, the type and the geometry of the tillage equipment (Moitzi et al. 2014). The retention of crop residue at the soil surface can result in an increase in carbon and nitrogen concentrations in the uppermost 50 mm of soil (Kahlon et al. 2013). The study by Karlen et al. (2013) highlighted, that long-term use of mouldboard ploughing and associated secondary tillage operations has a negative impact on soil quality/health indicators such as soil organic carbon. On the Canadian prairies and in cover crop-based arable cropping systems, studies have found that soil organic carbon stocks increase in surface soils with no-till (NT) relative to conventional tillage (CT) (Lafond et al. 2011). When combined with residue retention, NT increased soil organic carbon content and accelerated organic matter decomposition compared to CT in a Mediterranean loamy soil (Fuentes et al. 2012). In Northern India, Parihar et al. (2016) showed that over seven years, the soil carbon content in no tillage treatments was 35% higher at 0-150 mm and 25% higher at 150-300 mm than that in conventionally ploughed treatments.

Earthworms are important for improving soil condition as the creation of horizontal and vertical burrows can improve soil porosity and aeration (Bhadauria and Saxena 2010) and the creation of macro-pores can increase water infiltration rates in silty soils after compaction (Luise et al. 2013). Earthworms can also increase soil organic matter decomposition, release nutrients into solution (Singh and Kaur 2012), mix soil layers to incorporate organic matter, and they are associated with greater levels of soil microbial (bacterial and fungal) activity (Eriksen-Hamel et al. 2009). The most common UK earthworm species are *Allolobophora chlorotica* and *Lumbricus terrestris*, especially in neutral to base-rich grasslands and arable soils (Jones and Eggleton 2014).

Surface residues can improve soil structure as the surface organic matter can increase soil aggregation and protect soil aggregates from raindrop impact. The proportion of water stable aggregates is a good indicator of soil structure, which is determined by the rearrangement, flocculation and cementation of particles (Six et al. 2000; Bronick and Lal 2005), and this is a useful indicator of soil quality (Andrews et al. 1996). Paul et al. (2013) reported that at 0-150 mm soil depth, the number of macro-aggregates was consistently greater under reduced tillage compared to conventional tillage. Roldán et al. (2007) also concluded that soil aggregation, along with greater soil organic carbon, was greater under no tillage than with mouldboard ploughing in Mexico. The above research demonstrates that conservation tillage, compared to ploughing, can increase the level of soil organic matter in the surface layers, the abundance of deep dwelling earthworms and the proportion of water stable aggregates. However, there is less research that compares different forms of conservation tillage. The objective of the current study was to determine the effect of five treatments comprising commercially-available conservation tillage drills on crop residue levels and soil properties. A companion paper by Giannitsopoulos et al. (2019) has reported on the effect of conservation tillage drills on crop yields.

2. Materials and Methods

2.1 Site description and meteorology

The experiment was undertaken on two 4-ha fields, at Lamport Hall Estate (52°35'85"N 0.87°25'63"W), about 14 km north of Northampton in the United Kingdom. The soil type varied between the two fields. In one field, labelled “clay loam”, the soil had a clay loam texture, a red colour, a base saturation greater than 50%, and bedrock within 50 cm (Table 1). By contrast, in the other field, labelled “clay”, the soil had a clay texture and was prone to waterlogging (Table 1). The mean soil texture measured in the clay loam field and the clay field corresponded with reference texture values for the Banbury and Denchworth Soil Series respectively (Cranfield University 2019; Table 1).

The experiment ran for three years from September 2013 to August 2016. The annual rainfall was 762 mm in the first year, declining to 485 mm and 631 mm in year 2 and 3 respectively (Table 2). The mean air temperature in the three seasons was 10.4-10.9°C, which is marginally warmer than the mean temperature of 10.2°C between 1981 and 2010 (Pitsford School Weather Station, 2017).

[Table 1]

[Table 2]

2.2 Experimental design and treatments

Within both the clay loam and the clay field, five contrasting conservation tillage treatments (Table 3) were compared in a randomized complete block design with four replicates per treatment within each field (Figure 1). Hence there were 20 experimental plots per field (width: 12 m; length: 100-200 m) and within each single plot there were four sampling locations. Winter wheat (*Triticum aestivum* L.) and winter oilseed rape (*Brassica napus* L.) were planted in an alternating rotation over three years. The most soil-disruptive conservation tillage treatment was the existing ‘Farm System’, which comprised a Sumo Trio stubble cultivator (Sumo UK Ltd, Yorkshire, UK) operating at a depth of 200 mm (Table 3; Figure 1). When the wheat was planted in the clay field in 2014 and in the clay loam

Accepted Article

field in 2013 and 2015, the Farm System comprised two passes of the Sumo Trio followed by a Kuhn seed drill (Figure 1). By contrast, for the oilseed rape the Farm System comprised a one-pass system of the Sumo Trio with a seed hopper attached. The next most disruptive system was the Sumo DTS (operating at a soil depth of 177 mm), followed by the Claydon Hybrid (Claydon Yield-o-Meter Ltd, Suffolk, UK) and Mzuri Pro-Til (Mzuri Ltd, Worcestershire, UK) systems, which both operated at 150 mm. The least disruptive system, termed the “Low Disruption” treatment, comprised the use of a Väderstad Rapid seed drill (Vaderstad Ltd, Lincolnshire, UK) for the wheat crop, and the Väderstad Seed Hawk (year 1) or Horsch Sprinter 6ST (Horsch UK Ltd, Cambridgeshire, UK) (years 2 and 3) for the oilseed rape. The plan was for crops in the same field to be planted on the same day (Table 4). However, in year 3 there was a 10-day delay in planting the oilseed rape in the clay loam field with the Sumo DTS and the Mzuri Pro Til, and a 10-day delay in planting the wheat in the clay field with the Sumo DTS (Table 4). Details of the wheat and oilseed rape yields from the five treatments have been reported by Giannitsopoulos et al. (2019).

[Table 3]

[Figure 1]

[Table 4]

2.3 Measurements

The coverage of crop residue on the soil surface was measured in 2014 and 2015 using a 1 m² quadrat grid (with 100 squares), at the start of the cropping season in each field, immediately after drilling (Table 5). The quadrat was placed in four pre-defined locations in each plot. The proportion of quadrat internodes aligning with surface crop residue was used to calculate the surface residue percentage. Total soil organic carbon (TOC) was measured at a depth of 0-50 and 150-200 mm in March 2014 and March 2016 for both fields, in a similar location to the crop residue measurements. However, because of resource limitations, soil organic carbon was not measured at 150-200 mm in the clay loam field in 2016. The procedure followed the dry combustion method (elementary analysis - British Standard BS 7755 Section 3.8:1995). It has been recognised that calculating organic

carbon storage as the product of carbon concentration, bulk density and soil thickness – the ‘fixed depth method’ – doesn’t fully account for changes in volume that could result from differences between treatments (Ellert and Bettany, 1995; Lee et al., 2009). Hence comparisons of TOC were expressed on a mass basis, and followed the equivalent soil mass (ESM) method of TOC calculation (Ellert & Bettany 1995; Shi et al. 2013). Using this method, changes in soil bulk density are normalised against a reference value. The reference soil bulk density can be based on the observed minimum or maximum (Lee et al. 2009) or an arbitrary value (Bambrick et al. 2010). In this study, the maximum observed bulk density of 1.7 Mg m^{-3} was selected for the calculation of the equivalent soil mass.

For a soil thickness T of 0.05 m, the actual soil mass ($M_{Soil,act}$; Mg ha^{-1}) and the equivalent soil mass ($M_{Soil,eq}$; Mg ha^{-1}) were calculated from Equation 1 using the measured actual ($\rho_{b,act}$) and the reference bulk density ($\rho_{b,ref} = 1.7 \text{ Mg m}^{-3}$) respectively.

$$M_{soil} = \rho_{b,act} * T * 10,000 \text{ m}^2 \text{ ha}^{-1} \quad \text{Eq. (1)}$$

The equivalent soil mass $M_{soil,eq}$ was 850 Mg ha^{-1} . The additional soil thicknesses (T_{add} ; m) required to attain the equivalent soil mass was then calculated using Equation 2:

$$T_{add} = \frac{(M_{Soil,eq} - M_{Soil,act})}{\rho_{b,ref} * 10,000 \text{ m}^2 \text{ ha}^{-1}} \quad \text{Eq. (2)}$$

The mass of carbon in the actual soil mass ($M_{C,Soil,act}$; Mg C ha^{-1}) and in the additional soil mass ($M_{C,Soil,add}$; Mg C ha^{-1}) was calculated using Equation 3 and Equation 4 respectively, where C is the measured soil organic carbon concentration (kg C Mg^{-1} soil).

$$M_{C,Soil,act} = C * \rho_{b,act} * T * 10,000 \text{ m}^2 \text{ ha}^{-1} * 0.001 \text{ Mg kg}^{-1} \quad \text{Eq. (3)}$$

$$M_{C,Soil,add} = C * \rho_{b,act} * T_{add} * 10,000 \text{ m}^2 \text{ ha}^{-1} * 0.001 \text{ Mg kg}^{-1} \quad \text{Eq. (4)}$$

Finally, the equivalent soil carbon mass per unit area ($M_{C,Soil,eq}$; Mg ha^{-1}) was calculated by summing $M_{C,Soil,act}$ and $M_{C,Soil,add}$ (Equation 5).

$$M_{C,Soil,eq} = M_{C,Soil,act} + M_{C,Soil,add} \quad \text{Eq. (5)}$$

The density of earthworms per square metre was measured following the BS EN ISO 23611-1:2011 method (Soil quality-Sampling of soil invertebrates) and the Open Air Laboratories Guide (Jones and Lowe, 2012). The density of earthworms was measured as follows: on the day before measurement, for each planned sample, 30 g of mustard powder was mixed in a container with 250 ml of water and held overnight at room temperature. In the field, a further 0.75 litres of water was added and shaken to ensure an even suspension (total volume = 1 litre). The soil from the square to 100 mm depth was then laid on a plastic sheet and the densities of juvenile and adult earthworms at 0-100 mm were counted. One litre of mustard liquid was then poured into the pit and the density of earthworms emerging from depths greater than 100 mm was measured over 15 minutes after the solution had soaked away. The individuals were categorised as either juveniles or adults; the latter were distinguished by the presence of a well-developed clitellum i.e. a belt- or saddle-like swollen area on the earthworm's body.

The proportion of soil aggregates that are stable in water (water stable aggregates; WSA) was determined for the uppermost 0-100 mm of soil each year in each field, using the wet sieving method (Low, 1954). Again, the samples were taken in a similar area to the residue measurements within each plot. The results were expressed as a percentage of the soil fraction between 3.35 mm and 5 mm. Statistical differences between treatment means were determined using ANOVA by the 'aov' function, and linear regression models were derived for each field using the 'lm' function, using the R Project for Statistical Computing (R Core Team 2017). In both situations, effects were considered significant if the p value was equal to or less than 0.05. Data mapping was carried out using ESRI-ArcMap 10.4.1.

[Table 5]

3. Results

3.1 Crop residue

On 9 October 2014, in the clay loam field, the coverage of crop residue on the surface ranged from a

minimum of 17% for the two pass Farm System to 78% for the Low Disruption system (Figure 2). The Sumo DTS (45%), Mzuri (52%) and Claydon (60%) systems gave intermediate results (Figure 2). On 2 October 2015, the Low Disruption system again produced the greatest ($p < 0.05$) coverage of crop residue (86%) followed by the Claydon (60%). In this case, because the Farm System in the oilseed rape was a one-pass rather than a two-pass system, the residue coverage with the one-pass Farm System (57%), Mzuri (55%) and Sumo DTS (54%) were similar to each other. On 19 September 2014 in the clay field, the crop residue coverage was greater ($p < 0.05$) in the Low Disruption system (79%) than the one-pass Farm System (72%), the Sumo DTS (70%) and the Mzuri (68%) treatments (Figure 2). The surface coverage with the Claydon (75%) was similar to the Low Disruption system and higher ($p < 0.05$) than the Mzuri (68%). On 23 October, the residue coverage significantly varied between each treatment, being lowest with the Farm System (15%), followed in ascending order by the Sumo DTS (48%), Claydon (52%), Mzuri (67%) and the Low Disruption system (82%).

[Figure 2]

3.2 Soil organic carbon

The total soil organic carbon was consistently greater in the soil surface (0-50 mm) than at 150-200 mm. Within the clay loam field there was no treatment effect ($p > 0.05$) on soil carbon, except in March 2014 at 150-200 mm, when the soil organic carbon content in the Sumo DTS treatment (23.5 kg Mg⁻¹ soil), was greater ($p < 0.05$) than that of the Farm System and Mzuri treatments (21.2 and 21.5 kg Mg⁻¹ soil respectively; data not shown). To better understand the equivalent soil carbon mass, the bulk density results from Giannitsopoulos (2017) are presented in Table 6. Even though the soil bulk density was greater with the Mzuri (1.37 Mg m⁻³) and Low Disruption (1.34 Mg m⁻³) than the Farm System (1.24 Mg m⁻³), there was no treatment effect on the equivalent soil carbon mass in year 1 (Table 6). In year 3 however, the treatment with the smallest soil bulk density showed the least equivalent soil carbon mass, specifically the equivalent soil carbon mass with the Farm System (14.7 Mg C ha⁻¹) was less than that of Claydon (16.6 Mg C ha⁻¹), Mzuri (16.8 Mg C ha⁻¹) and Low Disruption (17.2 Mg C ha⁻¹) treatments. Similarly, between March 2014 and March 2016, the Mzuri

and the Low Disruption showed a greater increase ($p < 0.05$) in equivalent soil carbon mass (1.11 Mg C ha⁻¹ and 0.48 Mg C ha⁻¹ respectively) than that of the Farm System which decreased by 2.45 Mg C ha⁻¹ (Table 6).

[Table 6]

3.3 Earthworm density

Earthworm (juveniles, adults and total densities) were measured in both fields. In general, across both fields, there were greater densities of earthworms at 0-100 mm than those that appeared from a depth greater than 100 mm. The juveniles were more abundant than adults at 0-100 mm, whereas adults outnumbered juveniles below this depth (Tables 7 and 8). The main species of earthworms were *Octolasion cyaneum*, *Lumbricus terrestris* and *Allolobophora chlorotica*. In the clay loam field, there was no effect of tillage treatment ($p > 0.05$) on the density of earthworms at greater than 100 mm depth, but there were effects ($p < 0.05$) at 0-100 mm (Table 7). In December 2014, the highest density of juveniles and adults at 0-100 mm depth appeared in the Low Disruption treatment (156 and 36 m⁻² respectively).

[Table 7]

Overall the total density of juvenile worms (at 0-100 mm and at greater than 100 mm depth) for the Low Disruption (161 m⁻²) was greater than in the Farm System and Sumo DTS (83 and 89 m⁻²), which in turn were greater than those in the Claydon and Mzuri (44 and 50 m⁻²) treatments (Table 7). The grand total density of worms in December 2014 was greater ($p < 0.05$) in the Low Disruption treatment (228 m⁻²) than for any of the other treatments. The density of earthworms in the Claydon treatment (63 m⁻²) was lower ($p < 0.05$) than those with the Farm System and the Sumo DTS (115 and 131 m⁻² respectively). In November 2015, the same response was also observed, with the greatest density of juveniles found in the Low Disruption treatment (164 m⁻²) at 0-100 mm depth. In the clay field, earthworms were counted in each of three years. The greatest treatment differences on earthworms at greater than 100 mm depth occurred in Year 3 (November 2015), when the density of adults was greatest in the Low Disruption treatment (44 m⁻²) and the density in

the Claydon treatment (26 m^{-2}) was greater than those with the Sumo DTS and the Farm System ($8\text{-}11 \text{ m}^{-2}$; Table 8). In terms of juvenile earthworms, at 0-100 mm in June 2014, the Low Disruption and Mzuri treatments ($125\text{-}127 \text{ m}^{-2}$) had more juveniles than the Farm System (64 m^{-2}) (Table 8). In November 2014, there was no treatment effect on overall earthworm densities, but there were more juvenile earthworms at 0-100 mm and fewer adults at greater than 100 mm depth when using the Claydon compared to most of the other treatments. In November 2015, the density of juveniles at 0-100 mm in the Low Disruption (111 m^{-2}) treatment was greater than that in the Farm System, Claydon and Sumo DTS treatments (range: $44\text{-}70 \text{ m}^{-2}$). The grand total density of earthworms for the Low Disruption was also significantly greater than that for the other treatments (Table 8).

[Table 8]

3.4 Water stable aggregates

In both the clay loam and the clay fields, there was no tillage treatment effect ($p > 0.05$) on the proportion of water stable aggregates in 2014 or 2015 (Table 9). However, in March 2016 in the clay loam field, the percentage of water stable aggregates was highest in the Low Disruption treatment (29.8%). In the clay field, although the overall effect of tillage treatment on water stable aggregates was not significant ($p = 0.10$), the highest value also occurred in the Low Disruption treatment (51%).

[Table 9]

4. Discussion

4.1 Crop residue

The Low Disruption tillage treatment (comprising the Väderstad Seed Hawk and Rapid and the Horsch Sprinter) resulted in the greatest cover of surface crop residue ($>70\%$), while the least cover occurred with the double pass Farm System (15-17%). The large residue values of the Low Disruption system can be related to its shallow working depths (25-100 mm) which result in less soil disturbance than the other tillage treatments. By contrast, the two pass Farm System in wheat caused the most soil disturbance. The first pass with the Sumo Trio worked deeper (200 mm) than the other systems and the Kuhn HR seed drill included a power harrow, which disturbed and mixed

the soil surface. These results demonstrate that crop residue coverage can vary between non-inversion tillage systems, and are consistent with the findings of Olaoye (2001) and López et al. (2003) who showed that both deep and two-three passes conservation tillage systems resulted in less crop residue on the soil surface. Rasnake (1983) also reported that whereas the use of a chisel and disc reduced residue on the surface by one-third, no-tillage left almost all the residue on the soil surface. It has been argued that such no-tillage systems, that retain vegetative cover, can increase the sequestration of carbon in the soil surface (Charman and Murphy, 2007).

4.2 Soil organic carbon

In the clay field, between 2014 and 2016, the Mzuri and the Low Disruption systems resulted in a significantly greater increase in the surface (0-50 mm) total soil organic carbon (+1.11 and +0.48 Mg C ha⁻¹ respectively) than the Farm System, where it was reduced by 2.4 Mg C ha⁻¹. This can be related to the Low Disruption and the Mzuri systems leaving a greater amount of crop residue on the soil surface than the Sumo DTS and the Farm System. A linear regression analysis (Equation 6; Annex: Figure A) within the clay field in year 3 demonstrated a significant ($p < 0.05$) positive slope of the effect of crop residue (%) on the total soil organic carbon (TOC; %) ($R^2 = 0.06$; $n = 80$; $p < 0.05$).

$$\text{TOC} = 0.004 (\pm 0.002) \times \text{Crop residue} + 2.6 (\pm 0.1) \quad \text{Eq. (6)}$$

Equation 6 indicates that, every 10% increase in crop residue left on the soil surface, was associated with an increase in total soil organic carbon of 0.04% (or 0.4 kg C Mg⁻¹ soil) in the top 50 mm. This is equivalent to an increase of 0.24 Mg C ha⁻¹ in the top 50 mm of soil assuming a soil bulk density of 1.2 Mg m⁻³. Huang et al. (2015) reported that a no-tillage system with straw cover, increased total soil organic carbon content at 0-50 mm depth by 2.9 t C ha⁻¹ (0.3 t C ha⁻¹ yr⁻¹) in the Yellow River Delta in China when compared to conventional ploughing in a 9-year study. In addition, Al-Kaisi and Yin (2005) pointed out that in Iowa in the USA at 0-50 mm, strip-tillage and no-tillage significantly

increased total soil organic carbon by 4.6 and 4.7 Mg C ha⁻¹ within 3-years respectively (1.5 t C ha⁻¹ yr⁻¹), compared with deep rip tillage within a three-year experiment.

4.3 Earthworms

The Low Disruption system generally resulted in a greater density of earthworms compared to the other conservation tillage treatments in both fields. This could be a result of the minimal level of disturbance, but it could also be a result of the high level of surface residue cover. A linear regression analysis in the clay field in year 3 indicates a significant positive slope ($p < 0.01$) and intercept ($p < 0.001$) for the relationship between crop residue cover and earthworm abundance (Annex: Figure B). The analysis ($R^2 = 0.27$; $n = 80$; $p < 0.01$) indicated that higher crop residue coverage on the soil surface was associated with higher earthworm density. Equation 7 suggests that for every 10% increase in crop residue left on the soil surface, there will be 15 more earthworms per metre square.

$$\text{Earthworms (m}^{-2}\text{)} = 1.5 (\pm 0.3) \times \text{Crop residue (\%)} + 45.7 (\pm 15.7) \quad \text{Eq. (7)}$$

This is in line with Nieminen et al. (2011) who highlighted that conservation tillage and residue retention in Finland are both important for maintaining a stable soil environment (less physical disruption and higher moisture content respectively) that favors earthworms. A positive relationship between crop residues and earthworm abundance was also reported in a review by Turmel et al. (2015). Furthermore, Eriksen-Hamel et al. (2009) underlined that in Canada the effect of crop residue on earthworms and other soil fauna can vary depending on tillage frequency, plough depth, degree of residue incorporation, and crop residue type, amount and quality. The smaller earthworm abundance in the wheat crop with the Farm System compared to the other treatments can be attributed to the use of a two-pass disruptive tillage system with the wheat and a relatively less disruptive single pass system when oilseed rape was established. This is in agreement with Mullins

(2004), who highlighted that greater tillage intensity reduced earthworm growth and survival, and that the mean weight of the sampled earthworms decreased with an increasing number of tractor passes. Eriksen-Hamel et al. (2009) reported that tillage and residue management practices that increase soil organic carbon provide more organic substrates for earthworm growth, and that the greatest earthworm growth rates occurred in soils from reduced tillage treatments with large residue input.

4.4 Water stable aggregates

The mean percentage of water stable aggregates in the clay field (range: 38.7-45.3%) was greater than that in the clay loam field (24.4-28.4%). Water stable aggregates can be formed when soil organic carbon interacts with clay fractions and soil biology. In the clay loam field in the third year, the Low Disruption tillage treatment showed the greatest percentage of water stable aggregates ($p < 0.05$). Although the effect was not significant ($p > 0.05$), the same treatment also resulted in the largest value in the clay field. There was no significant relationship between earthworm abundance and the proportion of water stable aggregates. However linear regression analysis indicates a significant ($p < 0.001$) positive slope for the relationship between water stable aggregates and total soil organic carbon in the clay field in year 3 for each treatment (Equation 8; Annex: Figure C) ($R^2 = 0.22$; $n = 80$; $p < 0.001$).

$$\text{Water stable aggregates (\%)} = 14.8 (\pm 3.2) \times \text{TOC (\%)} + 3.5 (\pm 9.2) \quad \text{Eq. (8)}$$

Equation 8 suggests that a 1% increase ($10 \text{ kg Mg}^{-1} \text{ soil}$) in total soil organic carbon is associated with a 15% increase in the percentage of water stable aggregates. This is in agreement with Choudhury et al. (2014) who also reported that over a time period of five years, residue retention in non-inversion tillage systems in Haryana, India led to a 15.6% increase in the proportion of total water stable aggregates at the soil surface (0-150 mm) and 7.5% in the sub-surface soil (150-300 mm).

Accepted Article

As demonstrated by Equation 6, treatments that increase the percentage of surface crop residue cover after tillage tend to increase total soil organic carbon. This in turn tends to increase the source of food for soil organisms like earthworms, so that populations can increase. Among other benefits, the increase in soil carbon can also act as a glue or binding agent, which in turn will increase the stability of aggregates, which is often considered as a soil quality indicator. This is in line with Six et al. (2004) who linked a proportion of the soil carbon lost upon soil disturbance to the increased turnover (breakdown) of macro-aggregates.

5. Conclusions

The tillage treatments which left the greatest amount of crop residue on the soil surface also showed the greatest increase in the total soil organic carbon in the surface layer. The general relationship for the clay field was that, if a tillage drill manages to increase the surface residue by 10%, that would increase the soil's organic carbon at 0-50 mm depth, by 0.4 kg C Mg⁻¹ soil or 0.24 Mg C ha⁻¹. Retention of crop residue also increased earthworm abundance, with a 10% increase in crop residue in the clay field associated with an additional 150,000 earthworms per hectare. Lastly, a well-structured soil depends on soil aggregation. In the third year of the experiment in the clay loam field, the treatment that left the most crop residue on the soil surface had a greatest proportion of water stable aggregates compared to all the other treatments. In turn, well-aggregated soils, characterised by a network of micro-, meso- and macropores, should provide crops with access to air, water and nutrients needed for optimal growth.

Acknowledgements

We thank Frontier Agriculture Ltd who funded the study and the support of Lamport Hall Preservation Trust, Berrys Land Agents, and James Littlemore at Moulton College. We also acknowledge the technical help of Mick Stephens in the field operations.

6. References

- Álvaro-Fuentes, J., Easter, M., Paustian, K. 2012. Climate change effects on organic carbon storage in agricultural soils of northeastern Spain. *Agriculture, Ecosystems & Environment*. 155, 87–94.
- Al-Kaisi, M. M., Yin, X. 2005. Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn–soybean rotations. *Journal of Environment Quality*. 34, 437–445.
- Andrews, S. S., Karlen, D. L. and Cambardella, C. A. 1996. The Soil Management Assessment Framework. *Soil Sci. Soc. Am. J.*68, 1945–1962.
- Bambrick, AD, Whalen, JK, Bradley, RL, Cogliastro, A, Gordon, AM, Olivier, A, and Thevathasan, NV. 2010. Spatial heterogeneity of soil organic carbon in tree-based intercropping systems in Quebec and Ontario, Canada. *Agroforestry Systems*. 79 (3), 343–353.
- Bhadoria, T., Saxena, K.G. 2010. Role of earthworms in soil fertility maintenance through the production of biogenic structures. *Applied and Environ. Soil Sci.*2010, 1–7.
- Blanco-Canqui, H., Lal, R. 2007. Soil structure and organic carbon relationships following 10 years of wheat straw management in no-till. *Soil and Tillage Research*. 95, 240–254.
- Blum, W. E. H. 2005. Functions of Soil for Society and the Environment. *Reviews in Environmental Science and Bio/Technology*. 4, 75–79.
- Brandão, M., Milà i Canals, L., Clift, R. 2011. Soil organic carbon changes in the cultivation of energy crops: Implications for GHG balances and soil quality for use in LCA. *Biomass and Bioenergy*. 35, 2323–2336.
- Bronick, C.J., Lal, R. 2005. Soil structure and management: a review. *Geoderma* 124, 3–22.
- CEC 2006. Thematic strategy for soil protection. In: Technical Report COM 231. Commission of the European Communities. Brussels, Belgium. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52006DC0231&from=EN> (Accessed: 17 April 2018)
- Charman, P. E. V. and Murphy, B. W. 2007. *Soils: their properties and management*, South Melbourne: Oxford University Press (3rd ed.). Available at: <https://www.worldcat.org/title/soils-their-properties-and-management/oclc/85504139>

(Accessed: 17 April 2018).

- Chatskikh, D., Olesen, J. E., Hansen, E. M., Elsgaard, L., Petersen, B. M. 2008. Effects of reduced tillage on net greenhouse gas fluxes from loamy sand soil under winter crops in Denmark. *Agriculture, Ecosystems & Environment*. 128, 117–126.
- Choudhury, S.G., Sivastava, S., Singh, R., Chaudhari, S.K., Sharma, D.K., Singh, S.K., Sarkar, D. 2014. Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice–wheat cropping system under reclaimed sodic soil. *Soil Tillage Res.* 136,76–83.
- Cranfield University 2019. LandIS. Accessible Soil Information for England and Wales, United Kingdom. <https://www.cranfield.ac.uk/themes/environment-and-agrifood/landis>
- CTIC 2002. Tillage Type Definitions, Conservation Technology Information Center. <http://www.conservationinformation.org/resourcedisplay/322/> [Accessed 10 December 2017]
- Doran, J. W., Stamatiadis, S. I., Haberern, J. 2002. Soil health as an indicator of sustainable management. *Agriculture, Ecosystems & Environment*. 88, 107–110.
- Ellert, B.H. & Bettany, J.R. 1995. Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Science*. 75, 529–538.
- Eriksen-Hamel, N. S. Speratti, A.B., Whalen, J.K., Légère, A., Madramootoo, C.A. 2009. Earthworm populations and growth rates related to long-term crop residue and tillage management. *Soil Tillage Res.* 104, 311–316.
- FAO 2015. World Reference Base for Soil Resources 2014: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. Update 2015. <http://www.fao.org/3/i3794en/i3794en.pdf>
- Giannitsopoulos, M.L. 2017. Optimizing Conservation Tillage Systems for Wheat and Oilseed Rape Production. PhD Dissertation, Cranfield University, UK. <https://dspace.lib.cranfield.ac.uk/handle/1826/13661>
- Giannitsopoulos, M. L., Burgess, P. J., Rickson, R. J., 2019. Effects of conservation tillage systems on

soil physical changes and crop yields in a wheat–oilseed rape rotation. *Journal of Soil and Water Conservation*, 74, 247-258.

Huang, M., Liang, T., Wang, L., Zhou, C. 2015. Effects of no-tillage systems on soil physical properties and carbon sequestration under long-term wheat–maize double cropping system. *Catena*, 128, 195–202.

Jones, D., Lowe, C. 2012. Key to common British earthworms.

<https://www.opalexplornature.org/sites/default/files/7/file/soil-survey-field-guide-2014.pdf>

[Accessed 14 October 2017]

Jones, D.T., Eggleton, P. 2014. Earthworms in England: Distribution, Abundance and Habitats.

Natural England Commissioned Report NERC145.

<http://publications.naturalengland.org.uk/file/5824256822738944> [Accessed 14 October 2017]

Kahlon, M. S., Lal, R., Ann-Varughese. M. 2013. Twenty-two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. *Soil Tillage Res. Elsevier B.V.*, 126, pp. 151–158.

Karlen, D.L., Mausbach, J.M., Doran, J.W., Cline,R.G., Harris,R.F., and Schuman, G. E. 1997. Soil Quality: A Concept, Definition and Framework for Evaluation (A Guest Editorial). *Soil Sci. Soc. Am. J.* 61, 4 – 10.

Karlen, D. L., Andrews, Susan S., Wienhold, Brian J., Zobeck, Ted M. 2008. Soil Quality Assessment: Past, Present and Future.*J. Integr. Biosci.* 6(1), 3–14.

Karlen, D. L., Cambardella, C. A., Kovar, J. L., Colvin, T. S. 2013. Soil quality response to long-term tillage and crop rotation practices. *Soil & Tillage Research.* 133, 54–64.

Lal, R. 2004. Soil carbon sequestration to mitigate climate change. *Geoderma*, 123, 1-22

Lal, R. 2015. Restoring Soil Quality to Mitigate Soil Degradation. *Sustainability*, 7, 5875–5895.

Lafond, G. P., Walley, F., May, W. E., Holzapfel, C. B. 2011. Long-term impact of no-till on soil properties and crop productivity on the Canadian prairies. *Soil & Tillage Research.* 117, 110–

123.

- Lee, J, Hopmans, JW, Rolston, DE, Baer, SG, and Six, J. 2009. Determining soil carbon stock changes: Simple bulk density corrections fail. *Agriculture, Ecosystems & Environment*, 134 (3-4), 251-256.
- López, M. V., Moret, D., Gracia, R., Arrúe, J L. 2003. Tillage effects on barley residue cover during fallow in semiarid Aragon. *Soil Tillage Res.* 72, 53–64.
- Low, A. J. 1954. The study of soil structure in the field and the laboratory. *Journal of Soil Science*. Blackwell Publishing Ltd, 5(1), 57–74.
- Luise, M. Bartz, C., Pasini, A., Gardner, G. 2013. Earthworms as soil quality indicators in Brazilian no-tillage systems. *Applied Soil Ecology*. Elsevier B.V., 69, 39–48.
- Moitzi, G., Wagenstrisl, H., Refenner, K., Weingartmann, H., Piringer, G., Boxberger, J., Gronauer, A. 2014. Effects of working depth and wheel slip on fuel consumption of selected tillage implements. *Agric Eng Int: CIGR Journal*, 16(1), 182–190.
- Mullins, C. E. 2004. Managing soil and roots for profitable production Soil problems worldwide and their solution: lessons for UK agriculture, In HGCA conference 2004: Managing soil and roots for profitable production. [Accessed 14 October 2017]
<http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.565.1920&rep=rep1&type=pdf>
- Muñoz-Rojas, M., Erickson, T. E., Dixon, K. W., Merritt, D. J. 2016. Soil quality indicators to assess functionality of restored soils in degraded semiarid ecosystems. *Restoration Ecology*. 24, S43–S52.
- Nieminen, M., Ketoja, E., Mikola, J., Terhivuo, J., Sirén, T., Nuutinen, V. 2011. Local land use effects and regional environmental limits on earthworm communities in Finnish arable landscapes, *Ecological Applications*. Ecological Society of America, 21(8), 3162–3177.
- Nimmo, J. R., 2004: Porosity and pore size distribution. *Encyclopedia of Soils in the Environment*, 295–303.
- OECD 2001. *Environmental Indicators for Agriculture. Volume 3 Methods and Results*. Paris: OECD.

<https://www.oecd.org/tad/sustainable-agriculture/40680869.pdf> [Accessed 14 October 2017]

- Olaoye, J. O. 2001. Influence of tillage on crop residue cover, soil properties and yield components of cowpea in derived savannah ectones of Nigeria. *Soil Tillage Res.* 64, 179-187.
- Parihar, C. M., Yadav, M. R., Jat, S. L., Singh, A. K., Kumar, B., Pradhan, S., Chakraborty, D., Jat, M. L., Jat, R. K., Saharawat, Y. S., Yadav, O. P. 2016. Long-term effect of conservation agriculture in maize rotations on total organic carbon, physical and biological properties of a sandy loam soil in north-western Indo-Gangetic Plains. *Soil Tillage Res.* 161, 116–128.
- Paul, B. K., Vanlauwe, B., Ayuke, F., Gassner, A., Hoogmoed, M., Hurisso, T.T., Koala, S., Lelei, D., Ndabamenye, T., Six, J., Pulleman, M.M. 2013. Medium-term impact of tillage and residue management on soil aggregate stability, soil carbon and crop productivity. *Agric. Ecos. Env.* Elsevier B.V., 164, 14–22.
- Pitsford School Weather Station 2017. <http://www.northantsweather.org.uk/> [Accessed 14 October 2014]
- R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL <https://www.R-project.org/>
- Rabot, E., Wiesmeier, M., Schlüter, S., Vogel, H. J. 2018. Soil structure as an indicator of soil functions: A review. *Geoderma.* 314, 122–137.
- Rasnake, M. 1983. Tillage and Crop Residue Management. Agriculture and Natural Resources Publications. http://uknowledge.uky.edu/anr_reports/ [Accessed 14 October 2017]
- Roldán, A., Salinas-García, J.R., Alguacil, M.M., Caravaca, F. 2007. Soil sustainability indicators following conservation tillage practices under subtropical maize and bean crops. *Soil Tillage Res.* 93(2), 273–282.
- Shi, S, Zhang, W, Zhang, P, Yu, Y, and Ding, F. 2013. A synthesis of change in deep soil organic carbon stores with afforestation of agricultural soils. *Forest Ecology and Management.* 296, 53-63.
- Singh, A. and Kaur, J. 2012. Impact of conservation tillage on soil properties in rice- wheat cropping system. *Agricultural sci. research journal*, 2, 30–41.

Six, J., Elliott, E. T., Paustian, K. 2000. Soil Structure and Soil Organic Matter: II. A Normalized Stability Index and the Effect of Mineralogy. *Soil Sci. Soc. Am. J.* 64, 1042–1049.

Six, J., Bossuyt, H., Degryze, S., Deneff, K. 2004. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil Tillage Res.* 79, 7–31.

Soane, B. D., Ball, B.C., Arvidsson, J., Basch, G., Moreno, F., Roger-Estrade, J. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. *Soil Tillage Res. Elsevier B.V.*, 118, 66–87.

Turmel, M.S., Speratti, A., Baudron, F., Verhulst, N., Govaerts, B. 2015. Crop residue management and soil health: A systems analysis. *Agricultural Systems*, 134, 6–16.

Table 1. Classification of the soils in each field using the World Reference Base (WRB) (FAO 2015), the UK soil series and referenced soil texture according to Cranfield University (2019), and the measured soil texture

Field	WRB classification	Soil series	Source of texture values	Clay (%)	Silt (%)	Sand (%)
Clay loam field	Eutric chromic endoleptic cambisol	Banbury	Referenced	25	30	45
			Measured	30.8	29.8	39.3
Clay field	Eutric vertic stagnosol	Denchworth	Referenced	43	40	17
			Measured	47.7	34.8	17.4

Table 2. Annual rainfall and mean annual temperature for each cropping season (from Pitsford School Weather Station, 2017)

Year	Rainfall (mm)	Temperature (°C)
1. Sep 13 - Aug 14	762	10.4
2. Sep 14 - Aug 15	485	10.4
3. Sep 15 - Aug 16	631	10.9

Table 3. The main implement type and the depth of operation, seed depth, and width of soil disturbance for each tillage treatment

Tillage treatment	Implement type	Depth of pass (mm)	Seed depth (mm)	Width of soil disturbance ^c (mm)
1. Farm System^a				
Sumo Trio	Tine	200	25	465
Followed by Kuhn HR	Combi-drill	100	25	>465 ^c
2. Sumo DTS	Tine	177	25	~ 200 ^c
3. Claydon Hybrid	Tine	150	25	235
4. Mzuri Pro-Til	Tine	150	25	300
5. Low Disruption^b				
Horsch Sprinter	Tine	100	25	< 100 ^c
Väderstad Rapid	Disc	25	20	87
Väderstad Seed Hawk	Tine	25	12	83

^a: The Farm System included the Sumo Trio and Kuhn seed drill for winter wheat and only the Sumo Trio for oilseed rape

^b: The Low Disruption system varied according to availability of equipment

^c: The width of disturbance of the main implement of each drill, apart from the Kuhn, the Sumo DTS and the Horsch was established in a soil bin. The estimated width of disturbance is around 200 mm for Sumo DTS and less than 100 mm for Horsch.

Table 4. Dates for applications of treatments to fields for three cropping seasons

Tillage treatment	Clay loam field			Clay field		
	2013	2014	2015	2013	2014	2015
	Oilseed rape	Wheat	Oilseed rape	Wheat	Oilseed rape	Wheat
Farm System	5 Sept	29 Sept ^a	9 Sept	1 Oct ^a	28 Aug	5 Oct ^b
Sumo DTS	5 Sept	29 Sept	18 Sept	23 Sept	28 Aug	23 Oct
Claydon Hybrid	5 Sept	29 Sept	8 Sept	23 Sept	28 Aug	13 Oct
Mzuri Pro Til	5 Sept	29 Sept	18 Sept	23 Sept	28 Aug	13 Oct
Low Disruption ^c	5 Sept	29 Sept	8 Sept	1 Oct	28 Aug	15 Oct

a: The Farm System included just the Sumo Trio for the oilseed rape, and the Sumo Trio and the Kuhn HR for the wheat crops.

b: In the Clay field in 2015, the Sumo Trio was used on 5 October and the Kuhn was used on 12 October.

c: The Low Disruption system used the Väderstad Rapid for the wheat, the Väderstad Seed Hawk for the oilseed rape in the clay loam field in 2013, and the Horsch Sprinter 6ST for the oilseed rape in 2014 and 2015.

Table 5. Sampling dates for the clay loam and clay field for crop residue, earthworms, total organic carbon (TOC) and water stable aggregates (WSA)

Parameter	Clay loam field			Clay field		
	2013-14	2014-15	2015-16	2013-14	2014-15	2015-16
Residue	-	9 Oct 14	2 Oct 15	-	19 Sep 14	23 Oct 15
TOC	20 Mar 14	-	10 Mar 16	19 Mar 14	-	11 Mar 16
Worms	-	6 Dec 14	26 Nov 15	15 Jun 14	29 Nov 14	28 Nov 15
WSA	20 Mar 14	21 Mar 15	10 Mar 16	19 Mar 14	22 Mar 15	11 Mar 16

Table 6. Mean values of total soil organic carbon (TOC) measured in March 2014 and March 2016, bulk density of the soil, measured on 20 September 2014 and 24 October 2015), and the equivalent soil carbon mass ($M_{C_{eq}}$ and derived change in soil carbon ($M_{C_{eq}}$) between 2014 and 2016 at 0-50 mm depth in the clay field

Treatment	2013-14 season			2015-16 season			$M_{C_{eq}}$ change (0-50 mm) (Mg C ha ⁻¹)
	TOC	Bulk density	$M_{C_{eq}}$	TOC	Bulk density	$M_{C_{eq}}$	
	(kg Mg ⁻¹ soil)	(Mg m ⁻³)	(Mg ha ⁻¹)	(kg Mg ⁻¹ soil)	(Mg m ⁻³)	(Mg ha ⁻¹)	
Farm System	26.31	1.24 b	17.2	27.10	1.09 b	14.7 b	- 2.45 c
Claydon Hybrid	25.94	1.33 ab	17.0	27.89	1.19 a	16.6 a	- 0.48 ab
Mzuri Pro-Til	24.39	1.37 a	15.7	28.29	1.19 a	16.8 a	+ 1.11 a
Sumo DTS	26.11	1.31 ab	16.9	27.14	1.17 a	15.8 ab	- 1.12 bc
Low Disruption	25.77	1.34 a	16.7	29.85	1.16 ab	17.2 a	+ 0.48 ab
<i>p value</i>	<i>NS</i>	< 0.05	<i>NS</i>	<i>NS</i>	< 0.05	< 0.05	< 0.05
Mean	25.70	1.33	16.7	28.05	1.16	16.2	-0.49

NS means not significant at $p=0.05$

Means with the same letter in a column are not significantly different at $p = 0.05$.

Table 7. Effect of tillage treatment and soil depth on the density of earthworms in the clay loam field

Date	Tillage treatment	Juveniles (m ⁻²)			Adults (m ⁻²)			Grand Total (m ⁻²)
		At 0-100 mm	At >100 mm	Total	At 0-100 mm	At >100 mm	Total	
Dec 2014	Farm System	80 b	3	83 b	17 b	15	32 bc	115 bc
	Sumo DTS	83 b	6	89 b	22 ab	20	42 b	131 b
	Claydon Hybrid	42 c	2	44 c	8 b	11	19 c	63 d
	Mzuri Pro Til	42 c	8	50 c	19 b	17	36 bc	86 cd
	Low Disruption	156 a	5	161 a	36 a	31	67 a	228 a
	<i>p value</i>	<0.05	NS	<0.05	<0.05	NS	<0.05	<0.05
Nov 2015	Farm System	95 b	8	103 b	14	26	40	143 b
	Sumo DTS	76 b	5	81 b	16	22	38	119 b
	Claydon Hybrid	65 b	8	73 b	23	25	48	121 b
	Mzuri Pro Til	89 b	6	95 b	19	26	45	140 b
	Low Disruption	164 a	8	171 a	19	28	47	218 a
	<i>p value</i>	<0.05	NS	<0.05	NS	NS	NS	<0.05

NS: not significant at $p < 0.05$; Means with the same letter within a column for a given date are not significantly different at $p = 0.05$

Table 8. Effect of tillage treatment and soil depth on the density for earthworms in the clay field

Date	Tillage treatment	Juveniles (m ⁻²)			Adults (m ⁻²)			Grand total (m ⁻²)
		At 0-100 mm	At >100 mm	Total	At 0-100 mm	At >100 mm	Total	
June 2014	Farm System	64 b	6	70 b	11	17	28	98 b
	Sumo DTS	95 ab	5	100 ab	23	14	37	137 ab
	Claydon Hybrid	103 ab	16	119 a	23	20	43	162 a
	Mzuri Pro Til	125 a	16	141 a	26	23	50	191 a
	Low Disruption	127 a	11	138 a	26	17	43	181 a
	<i>p value</i>	<0.05	NS	<0.05	NS	NS	NS	<0.05
Nov 2014	Farm System	45 b	5	50 b	61 ab	23	84	134
	Sumo DTS	45 b	14	59 b	73 a	33	106	166
	Claydon Hybrid	100 a	14	114 a	30 b	22	52	166
	Mzuri Pro Til	58 b	6	64 b	81 a	16	97	160
	Low Disruption	48 b	6	54 b	70 a	22	92	147
	<i>p value</i>	<0.05	NS	<0.05	<0.05	NS	NS	NS
Nov 2015	Farm System	44 c	5	48 d	16	11 c	26 c	75 c
	Sumo DTS	70 bc	9	80 bc	16	8 c	23 c	103 bc
	Claydon Hybrid	56 c	3	59 cd	33	26 ab	59 ab	119 b
	Mzuri Pro Til	94 ab	6	100 ab	17	20 bc	37 bc	138 b
	Low Disruption	111 a	5	116 a	28	44 a	72 a	188 a
	<i>p value</i>	<0.05	NS	<0.05	NS	<0.05	<0.05	<0.05

NS: not significant at $p < 0.05$; Means with the same letter within a column for a given date are not significantly different at $p = 0.05$

Table 9. Effect of tillage treatment and soil type on the proportion (%) of water stable aggregates

Tillage treatment	Water stable aggregates (%)					
	Clay loam			Clay		
	March 2014	March 2015	March 2016	March 2014	March 2015	March 2016
Farm System	24.3	27.3	25.3 b	39.9	42.4	43.3
Sumo DTS	25.1	25.9	24.9 b	39.3	42.0	44.3
Claydon Hybrid	22.7	25.8	22.7 b	39.5	41.0	43.6
Mzuri Pro Til	24.7	29.9	23.8 b	34.3	38.9	44.2
Low Disruption	25.5	33.2	29.8 a	40.6	43.1	51.0
<i>p value</i>	<i>NS</i>	<i>NS</i>	<i>< 0.05</i>	<i>NS</i>	<i>NS</i>	<i>NS</i>
Mean	24.4	28.4	25.3	38.7	41.5	45.3

NS means not significant at $p < 0.05$.

Means with the same letter within a column are not significantly different at $p = 0.05$

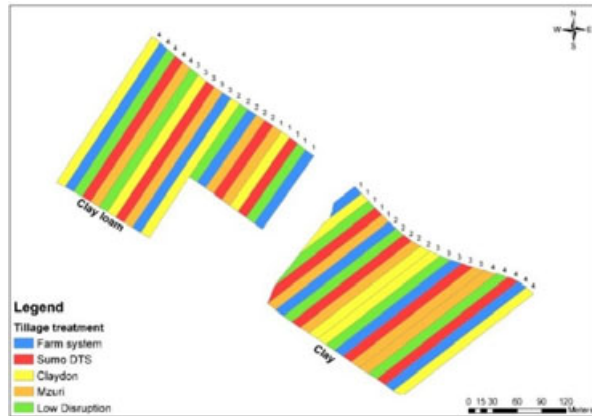


Figure 1. Schematic map of the distribution of each tillage treatment in the clay loam and clay fields (small numbers at the end of the plots indicate number of block)

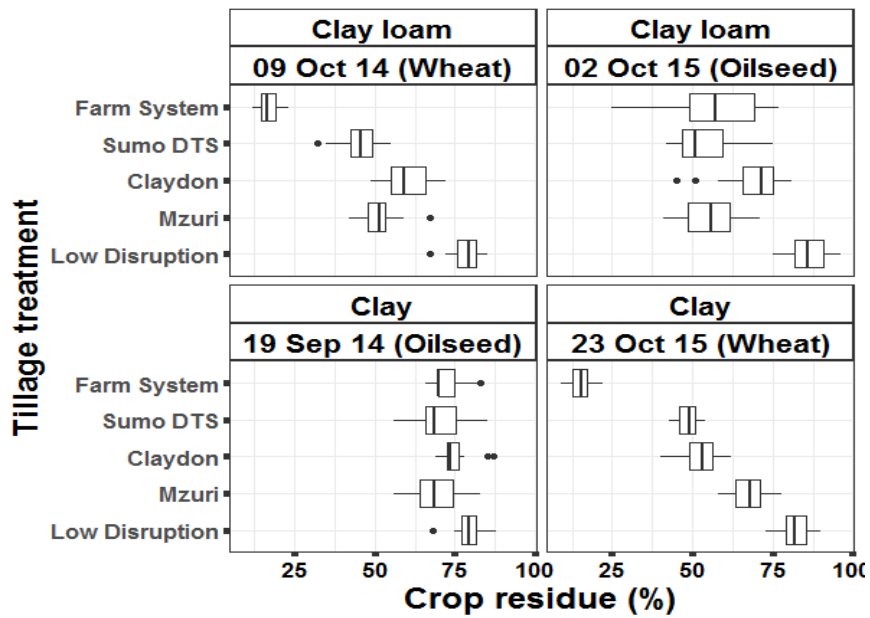


Figure 2. Effect of the five tillage treatments on the coverage of crop residue (%) on the soil surface for the clay loam and the clay fields in September-October 2014 and October 2015. Boxplot shows the spread of the data set (box = 25-75% of the data, line within box = median value, upper whisker = upper 25% of the data, lower whisker = lower 25% of the data, excluding outliers).

7. Annex

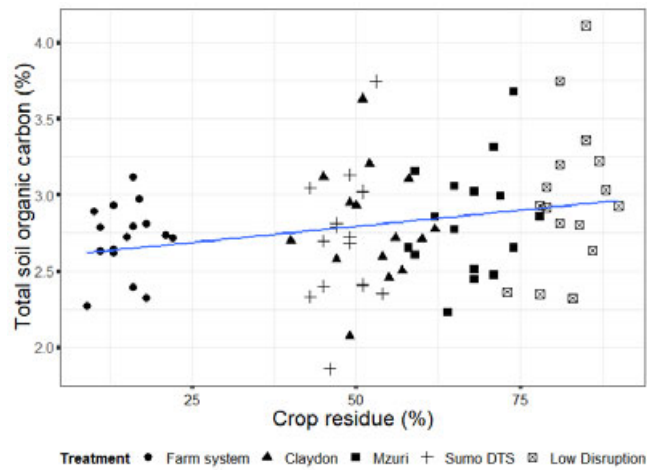


Figure A. Linear regression analysis between total soil organic carbon in the top 50 mm (TOC; %) in 2015-16 and the crop residue percentage in the clay field ($\text{TOC} = 0.004 (\pm 0.002) \times \text{Crop residue (\%)} + 2.6 (\pm 0.1)$; $R^2 = 0.06$; $n = 80$)

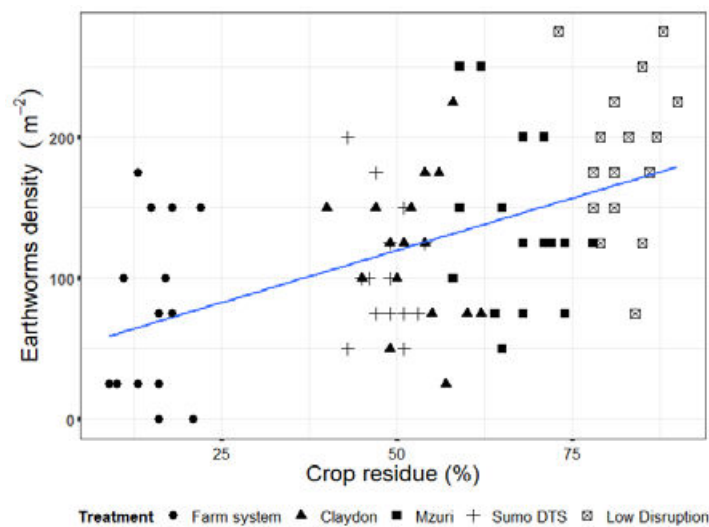


Figure B. Linear regression analysis between earthworms density (m^{-2}) and crop residue (%) in the clay field in 2015-16 ($\text{Earthworms (m}^{-2}\text{)} = 1.5 (\pm 0.3) \times \text{Crop residue (\%)} + 45.7 (\pm 15.7)$; $R^2 = 0.27$; $n = 80$)

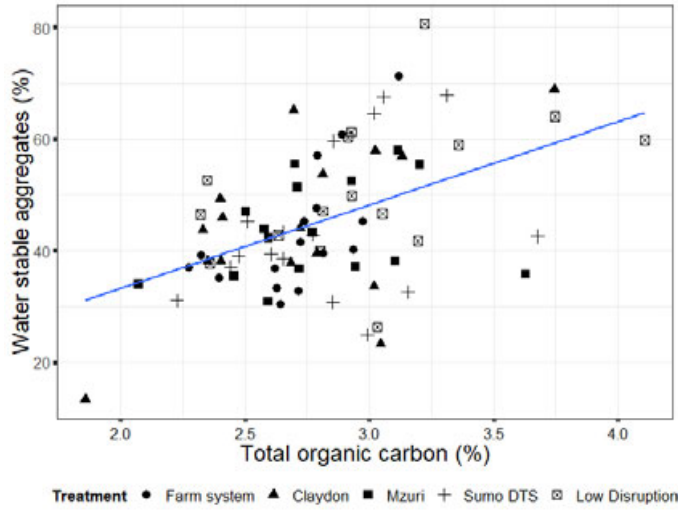


Figure C. Linear regression analysis between water stable aggregates (%) and the total soil organic carbon in the top 50 mm (TOC) in the clay field in 2015-16 (Water stable aggregates (%) = $14.8 (\pm 3.2)$ x TOC (%) + $3.5 (\pm 9.2)$; $R^2 = 0.22$; $n = 80$)