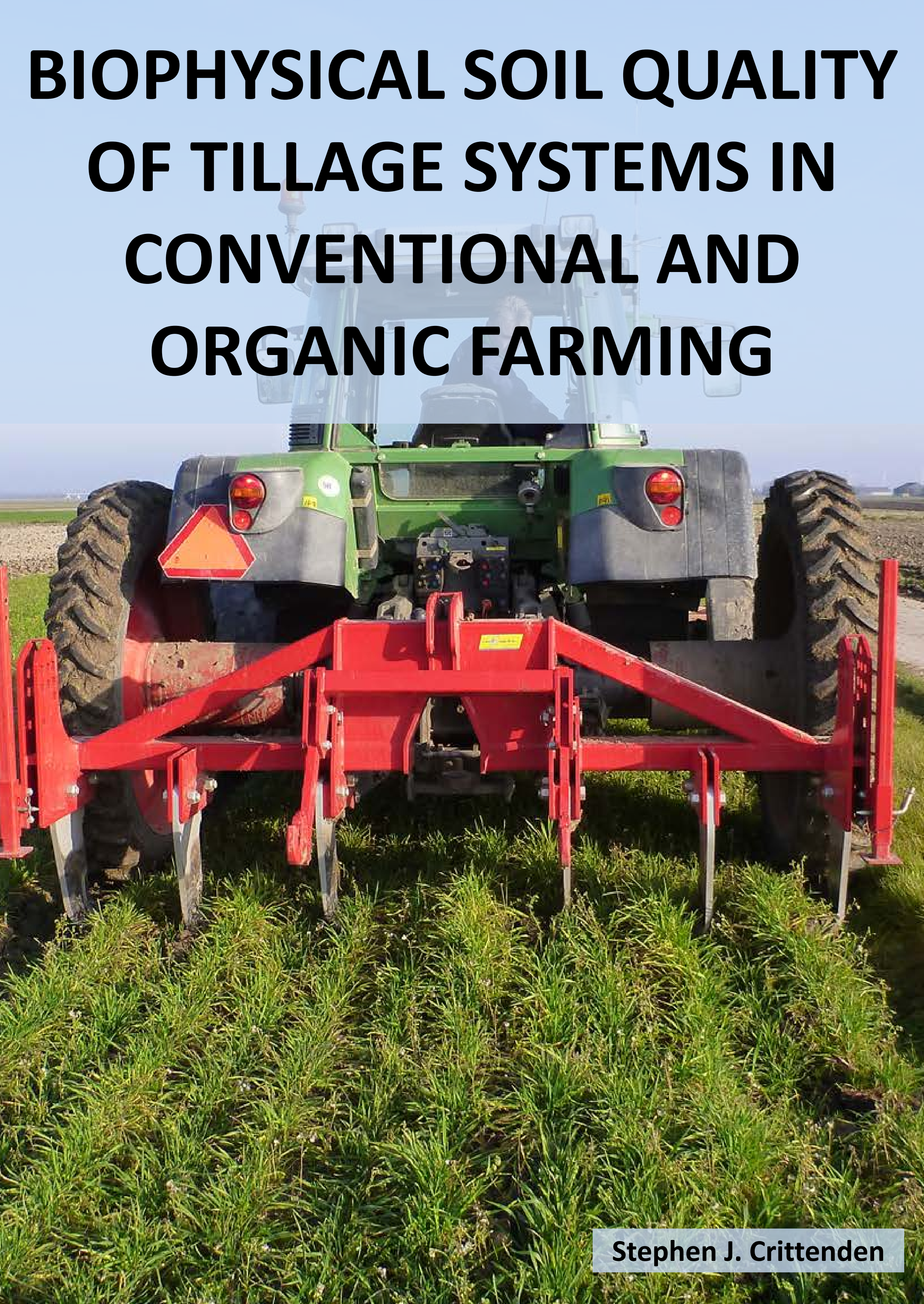
BIOPHYSICAL SOIL QUALITY OF TILLAGE SYSTEMS IN CONVENTIONAL AND ORGANIC FARMING



Stephen J. Crittenden

BIOPHYSICAL SOIL QUALITY OF TILLAGE SYSTEMS IN CONVENTIONAL AND ORGANIC FARMING

Thesis

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Biophysical Soil Quality of Tillage Systems in Conventional and Organic Farming

Stephen J. Crittenden

Thesis
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And what does the word quality mean? To me it means texture. This book has pores. It has features. This book can go under the microscope. You'd find life under glass, streaming past in infinite profusion. The more pores, the more truthfully recorded details of life per square inch you can get on a sheet of paper, the more 'literary' you are. That's my definition, anyway. Telling detail. Fresh detail. The good writers touch life often.

-Ray Bradbury, Fahrenheit 451

Contents

1

INTRODUCTION

1.1. BACKGROUND

Soil physical properties and soil biological activity are intertwined in their effects on soil ecosystem functioning. Increasing agricultural intensification and pressure put upon arable land for food security can hinder these soil ecosystem functions. Annual ploughing and use of heavy machinery, especially at sub-optimal soil water conditions, can cause compaction, loss of soil structure, and hence a reduction in soil physical functioning. Climate change predictions for the Netherlands forecast exacerbated soil water problems (KNMI, 2014). Wetter winter periods would lessen the windows of opportunity when soil water conditions are such that field operations can be done with minimal damage to soil structure. Crop growing seasons may experience longer drought periods interspersed with intensive rainfall events (KNMI, 2014), putting further pressure on soil to perform both water transmission and storage functions. Furthermore, this land-use intensification may decrease soil biodiversity, including earthworm abundance, biomass, and species diversity.

Soil management practices are being implemented to reduce soil structural degradation and stimulate soil biological activity, particularly earthworms and earthworm species abundances. Improved soil functioning may be achieved by allowing a more diverse earthworm community to construct a soil structure that will better perform beneficial ecosystem functions.

1.1.1. NON-INVERSION TILLAGE

Non-inversion tillage (Fig. 1.1) is a reduced tillage system used in The Netherlands adapted to typical Dutch crop rotations that include root and tuber crops. Conventional mouldboard ploughing inverts topsoil to prepare seedbeds, loosen soil, control weeds, and bury crop residues (Fig. 1.1). However, continuous ploughing destroys soil structure and changes soil hydrological functioning, compacts subsoil, decreases soil biodiversity, reduces soil organic matter and therefore leaves soil more susceptible to erosion. Non-inversion tillage therefore aims to improve soil structure and function, increase soil biodiversity that can support these physical functions, and reduce operating costs (Morris et al., 2010; Soane et al., 2012). Mouldboard ploughing and non-inversion tillage systems were compared in Chapters 2, 3, 4, 5, and the concluding Chapter 6 of this thesis.

Figure 1.1: Top image: Mouldboard ploughing, bottom image: non-inversion tillage using subsoiler on controlled-traffic lanes. Taken at PPO Lelystad research farm of Wageningen University and Research Centre

1.1.2. ORGANIC FARMING

Farming systems can have a large influence on soil physical properties and soil biology. Organic farming prohibits the use of synthetic fertilisers and pesticides, and increases the use of animal and green manures, diverse crop rotations, and mechanical weeding (Gomiero et al., 2011). Too few properly designed medium- to long-term studies have been conducted on reduced tillage systems in organic farming (Gadermaier et al., 2012; Irmler, 2010). Work presented in Chapters 2, 4, and 5 was all conducted on conventionally and organically farmed fields at the PPO Lelystad experimental farm ($52°32'N, 5°34'E$) of Applied Plant Research Wageningen UR, The Netherlands. Conventionally and organically managed fields were separated by at least 180 m and each field (n=4, in this thesis) contained plots of mouldboard ploughing, non-inversion tillage, and minimum tillage arranged in randomised complete block designs. Conventional and organic farming had unique crop rotations with each field within each farming type containing a different crop. Crop rotations were not the same between farming systems, were of different lengths, and were therefore not synchronised.

1.1.3. CONTROLLED TRAFFIC FARMING

Soil compaction in The Netherlands has been caused by use of heavy machinery for root-crop harvest in wet soil (Lamers et al., 1987). In addition to reducing tire pressure and machinery weight, a standardisation of wheel size and trafficking position has been proposed for agricultural practises to lessen soil compaction. Controlled traffic farming (CTF) proposes that all farm operations be conducted using permanent tracks at fixed positions (Vermeulen et al., 2010). Advances in GPS guidance systems has allowed for this. Farm machinery must therefore be adapted to fit onto tractors with the appropriate wheel spacing. CTF thus reduces soil compaction relative to random traffic in that farm operations are always conducted using fixed wheel tracks whereas traditionally each farm operation including ploughing, seeding, and harvesting might be carried out with different tractors with tire tracks and therefore soil compaction spread out across the soil surface. CTF is purported to lower production costs and increase yields due to better soil physical functioning (Vermeulen et al., 2010). CTF can improve soil porosity and thus lessen soil penetration resistance (Vermeulen and Mosquera, 2009). In no-till systems CTF has been found to reduce effective soil porosity hence lessening water infiltration, saturated hydraulic conductivity, and plant-available water (Blanco-Canqui et al., 2010). A seasonal CTF where harvesting and primary tillage are done normally but other practises including sowing, cultivation, liquid manure application, and weeding are done on controlled traffic lanes has been studied in The Netherlands (Vermeulen and Mosquera, 2009). This seasonal CTF is similar to that used at the PPO Lelystad research farm on the fields used in Chapters 2, 4, 5, and 6 of this thesis. The seasonal CTF used at PPO Lelystad was practised uniformly across all tillage treatments (mouldboard ploughing, non-inversion tillage, and minimum tillage) in both conventional and organic farming, so the effects of CTF could not be investigated separately. CTF may be even more beneficial in reduced tillage systems (i.e., non-inversion tillage and minimum tillage in this thesis) since the loosening effects of ploughing are removed and therefore the avoidance of soil compaction from farm operations becomes even more essential.

1.1.4. FIELD MARGIN STRIPS

Field margins border arable fields and contain diverse plant species and grasses with the objective of improving aboveground biodiversity (Dennis and Fry, 1992; Marshall, 2004). Field margin strips have been found to improve soil macrofaunal diversity and to provide populations of species, including earthworms, that colonise adjacent arable lands (Smith et al., 2008). In order for earthworm assemblages to influence soil functions they must first be present locally in the landscape and be able to colonize adjoining arable fields. The influence of field margin strips on earthworms in adjacent arable fields remains unclear however. On one hand Smith et al. (2008) and Hof and Bright (2010) showed higher earthworm numbers and diversity in field margin strips than in adjacent arable soil. On the other hand, Lagerlöf et al. (2002) found lower earthworm numbers in field margin strips than in adjacent arable soil. Very few studies have been published on earthworms in field margin strips, although the topic has been gaining attention in recent years. In order to capture landscape spatial heterogeneity and to confirm patterns seen at single research farms, earthworm assemblage monitoring should be done on multiple on-farm locations (Curry et al., 2002; Ernst and Emmerling, 2009; Marinissen, 1992). To catch temporal variation in earthworm numbers samplings should be done across multiple seasons and years (Pulleman et al., 2012; Roarty and Schmidt, 2013). Effects of field margin strips and reduced tillage on earthworm numbers and species abundances were investigated in Chapter 3.

1.2. SOIL PHYSICAL QUALITY

Soil physical quality as used in this thesis encompasses soil carbon which builds soil structure which results in soil physical functions. According to Topp et al. (1997), in terms of soil physical quality, the relevance of soil structure is that it controls soil water storage and transmission, aeration, and strength. There is growing concern in The Netherlands about soil physical conditions such as water logged soil that restricts trafficability, slaked soil from heavy precipitation events, and soil water holding capacity that will be exacerbated by further extremes in drought periods and precipitation events tied to climate change (KNMI, 2014). It is increasingly recognised that use of heavy farm machinery (e.g., harvesters) at suboptimal water conditions causes soil compaction and results in loss of soil physical and biological functioning.

Reduced soil tillage systems, such as the non-inversion tillage system in this thesis, strive to improve soil physical quality and stimulate soil biological activity, especially earthworms which relate to formation of soil structure. Reduced tillage can increase soil organic matter content, improve soil biodiversity, and reduce production costs (El Titi, 2003; Morris et al., 2010; Soane et al., 2012). Yearly mouldboard ploughing in autumn after main crop harvest (with or without cover crop) has been the standard practise in The Netherlands to control weeds, incorporate organic material (i.e., crop residues and manures), and loosen top soil to create a better seed bed. However, alternative tillage practises are being sought because yearly mouldboard ploughing, although it increases short-term soil porosity, changes soil structure by reducing soil aggregate stability, lowers soil water holding capacity, lessens soil organic matter content, and can compact subsoil (Bronick and Lal, 2005; Lal et al., 2007; Munkholm et al., 2008).

1.3. EARTHWORMS

Reduced tillage and controlled traffic may lessen the impact of heavy equipment on soil structure and function, opening a window of opportunity for soil's greatest engineers, earthworms, to construct a soil architecture that allows for soil water transmission and storage functions (Figure 1.2). Earthworm functional diversity may deliver a broader range of soil functions. Earthworm functional groups may play a role in the recuperation of soil structure and physical quality through their burrowing and casting activities. Earthworms are acknowledged to play major roles in many soil ecosystem functions such as decomposition and nutrient cycling, aeration, water infiltration, and soil structural formation (Blouin et al., 2013). Soil management strategies such as reduced tillage, organic farming, controlled-traffic farming, and field margin strips are expected to shift relative earthworm species abundances within those communities and therefore ecosystem functions will change. In addition, soil biodiversity, including earthworms, have an under valued and under appreciated relation with ecosystem services. In addition to soil biodiversity's direct influence on ecosystem functions there is added value

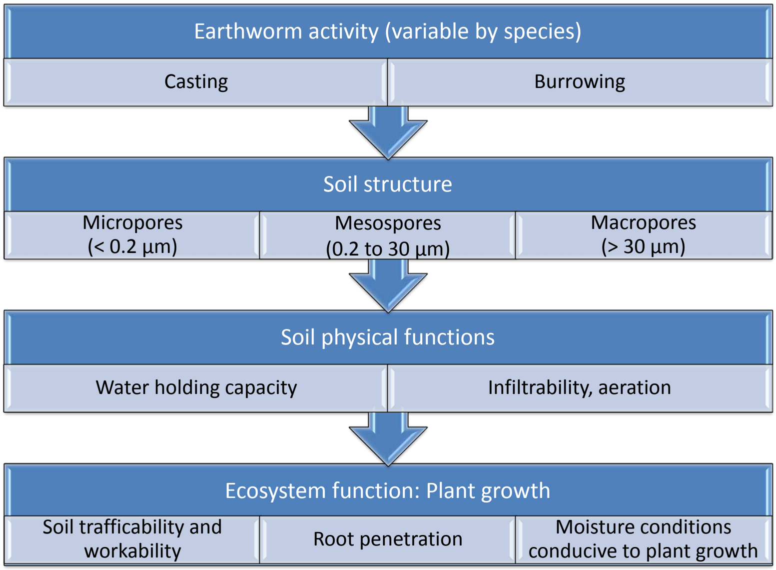


Figure 1.2: Representation of relations of earthworm activity, soil structure, soil physical function, and ecosystem functions. Adapted from Syers and Springett (1983) and Brown, Edwards, and Brussaard (2004)

in terms of mitigation and adaptation to environmental risk (i.e., fluctuations in deliverance of ecosystem services) (Pascual et al., 2015).

Reduced soil disturbance (tillage intensity and trafficking) may allow for an increase in earthworm functional diversity. However, it does not provide it inherently. Earthworm species must be present in the local landscape to take advantage of new or improved habitat in reduced tillage systems. Field margin strips conventionally have been used to promote above ground diversity and create habitat to increase pollination and natural enemies (disease and pest suppression) (Marshall, 1988). The below ground species diversity, in particular, that of earthworms is also being studied (Lagerlöf et al., 2002; Roarty and Schmidt, 2013; Smith et al., 2008). Field margin strips may promote migration of earthworms into adjacent arable land and subsequent related soil functions and ecosystem services.

1.4. THESIS OBJECTIVES

The work presented in this thesis aimed to evaluate the effects of (i) tillage systems in contrasting farming systems, (ii) and field margin strips on soil physical quality, including soil water and temperature dynamics, and on earthworm communities.

The overall thesis objectives were:

- to compare non-inversion tillage to the standard mouldboard ploughing practice in terms of soil physical functions, soil structural parameters, soil organic matter, and crop yield.

- to quantify the effects of non-inversion tillage and mouldboard ploughing on earthworm populations in conventional and organic farming.
- to compare reactions of soil water content to precipitation and soil temperature to ambient air temperature changes between non-inversion tillage and mouldboard ploughing in conventional and organic farming.
- to quantify the effects of field margin strips and non-inversion tillage on earthworm species assemblages across farms and cropping seasons.

1.5. THESIS OUTLINE

Chapter 2 evaluates earthworm abundance, biomass, and species abundances in a short-term study to ascertain the immediate impacts of ploughing, and monitors these same earthworm parameters in a 4-year study at the PPO Lelystad research farm of Wageningen University and Research Centre. To confirm and complement Chapter 2, a study of earthworms on private farms which encompasses the spatial variability on-farm across the landscape was conducted. Chapter 3 again examines earthworms in non-inversion tillage versus mouldboard ploughing systems, but this time in paired plots on four farms all with marine loam soil. In addition, Chapter 3 contains data on earthworms in field margin strips and their adjacent fields with the aim of ascertaining if the presumably higher and more diverse earthworm species assemblages in these strips then move into the nearby soils.

Chapters 2, 4, 5, and the concluding Chapter 6 of this thesis refer to distinct aspects of the evaluation of tillage systems in organic and conventional farming at PPO Lelystad. As mentioned above, Chapter 2 looks at soil biological quality (i.e., earthworms). Soil physical functions of soil water retention and field-saturated hydraulic conductivity and soil structural indicators, soil carbon, and crop yield are investigated in Chapter 4. The dynamics of soil water content and soil temperature are analysed in Chapter 5 using time-series analysis to comment on the reactions of these parameters to precipitation and ambient air temperature, respectively.

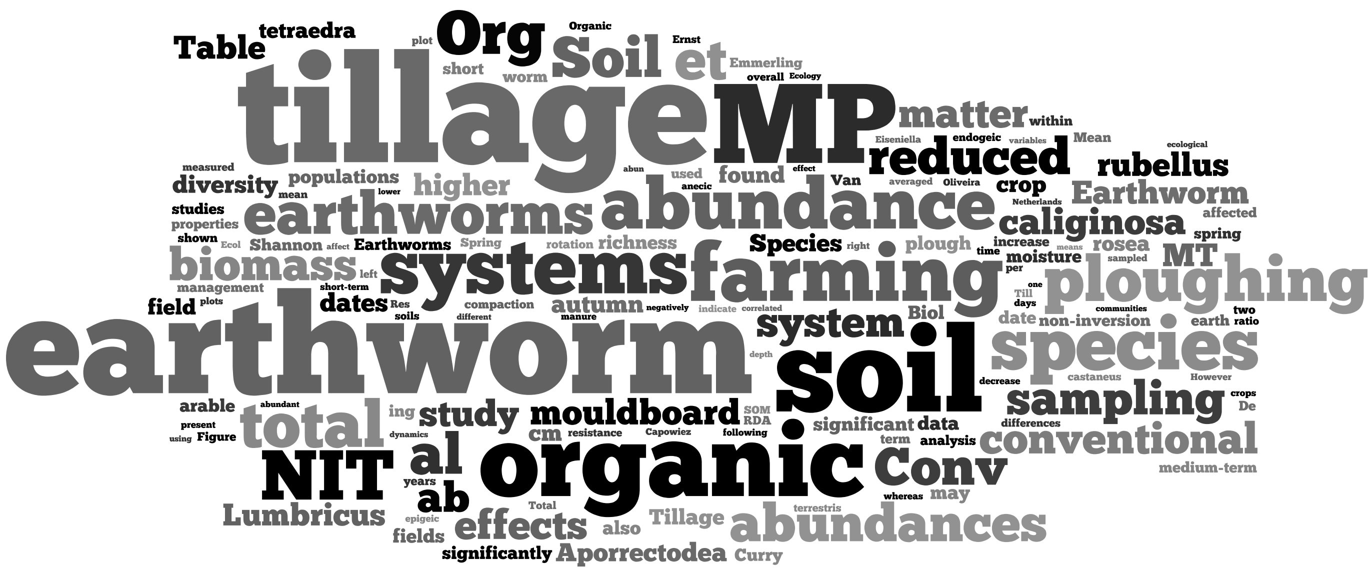
Chapter 6 presents an integrated analysis of physical and biological parameters. Data from Chapters 2 and 4 that had been gathered simultaneously were then combined in multivariate analyses to explore overall patterns in variation of physical and biological data as explained by tillage and farming systems. This integrated analysis attempts, in particular, to link earthworm species abundances with soil physical functions to test the hypothesis that the soil management practices studied of non-inversion tillage and organic farming have significant impact on these parameters.

Lastly, a general discussion is provided in which I systematically revisit the objectives mentioned in Section 1.4, where I make reference to the five main content chapters (Chapters 2, 3, 4, 5, and 6).

2

EFFECT OF TILLAGE ON EARTHWORMS OVER SHORT- AND MEDIUM-TERM IN CONVENTIONAL AND ORGANIC FARMING

This chapter has been published in Crittenden et al. (2014).



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Earthworms play an important role in many soil functions and are affected by soil tillage in agricultural soils. However, effects of tillage on earthworms are often studied without considering species and their interactions with soil properties. Furthermore, many field studies are based on one-time samplings that do not allow for characterisation of temporal variation. The current study monitored the short (up to 53 days) and medium term (up to 4 years) effects of soil tillage on earthworms in conventional and organic farming. Earthworm abundances decreased one and three weeks after mouldboard ploughing in both conventional and organic farming, suggesting direct and indirect mechanisms. However, the medium-term study revealed that earthworm populations in mouldboard ploughing systems recovered by spring. The endogeic species Aporrectodea caliginosa strongly dominated the earthworm community (76%), whereas anecic species remained <1% of all earthworms in all tillage and farming systems over the entire study. In conventional farming, mean total earthworm abundance was not significantly different in reduced tillage (153 m^{-2}) than mouldboard ploughing (MP; 130 m^{-2}). However, reduced tillage in conventional farming significantly increased the epigeic species Lumbricus rubellus from 0.1 m^{-2} in mouldboard ploughing to 9 m^{-2} averaged over 4 years. Contrastingly, in organic farming mean total earthworm abundance was 45% lower in reduced tillage (297 m^{-2}) than MP (430 m^{-2}), across all sampling dates over the medium-term study (significant at 3 of 6 sampling dates). Reduced tillage in organic farming decreased A. caliginosa from 304 m^{-2} in mouldboard ploughing to 169 m^{-2} averaged over 4 years (significant at all sampling dates). Multivariate analysis revealed clear separation between farming and tillage systems. Earthworm species abundances, soil moisture, and soil organic matter were positively correlated, whereas earthworm abundances and penetration resistance where negatively correlated. Variability demonstrated between sampling dates highlights the importance of multiple samplings in time to ascertain management effects on earthworms. Findings indicate that a reduction in tillage intensity in conventional farming affects earthworms differently than in organic farming. Differing earthworm species or ecological group response to interactions between soil tillage, crop, and organic matter management in conventional and organic farming has implications for management to maximise soil ecosystem functions.

2.1. INTRODUCTION

Earthworms affect many soil properties in agricultural land including nutrient availability, soil structure, and organic matter dynamics (Edwards, 2004). Earthworms in turn are influenced by soil moisture, organic matter, texture, pH, and soil management (Curry, 2004).

Tillage systems can affect soil biota through changes in habitat (van Capelle et al., 2012), loss of organic matter (Hendrix et al., 1992), moisture and temperature dynamics (Curry, 2004) and mechanical damage (Lee, 1985). Earthworm population change due to soil tillage depends on tillage intensity (Chan, 2001; Curry, 2004) and may be higher under root than cereal crops (Curry et al., 2002). Moreover, tillage may differentially affect earthworm species, depending on their feeding and burrowing behaviour. Earthworm species classified into ecological groups, defined by Bouché (1977), are epigeic that live on or near the soil surface, endogeic that live and feed in mineral soil, and anecic that are deep burrowing but feed at the soil surface (Sims and Gerard, 1999). Earthworm ecological groups affect soil processes to differing degrees and therefore have varying importance for ecosystem services (Keith and Robinson, 2012).

Conflicting tillage effects on earthworms have been presented in literature (Chan, 2001). On one hand, van Capelle et al. (2012), in a review of studies conducted in Germany, concluded that reduced tillage intensity increased earthworm abundances and species diversity. On the other hand, ploughing can positively influence endogeic species by increasing organic matter availability to them (Ernst and Emmerling, 2009), while it has the opposite affect on anecics (Capowiez et al., 2009). Many studies have focused on earthworms in no-tillage versus conventional ploughing systems in cereal crops, and have often not quantified earthworm species or their functional roles. Therefore, clarification is needed on tillage and arable soil management effects on earthworm species in a wider range of crop rotations.

Intermediate reduced tillage systems that de-compact, yet do not invert soil, are being implemented in arable systems where there is high soil compaction risk (e.g., root crops, high soil moisture). Non-inversion tillage systems, like other reduced tillage systems, are aimed at enhancing soil physical properties (e.g., structural stability, water retention) and soil organic matter (Morris et al., 2010), increasing soil biodiversity (El Titi, 2003), and reducing production costs (Soane et al., 2012). Soil compaction from tillage and field traffic can be detrimental to earthworms when it limits their burrowing activity (Capowiez et al., 2012; Langmaack et al., 1999). In particular, crops such as potatoes and sugar beets require the use of heavy machinery for land preparation and harvesting (Marinissen, 1992) which results in considerable soil disturbance (Buckerfield and Wiseman, 1997), especially under wet soil conditions. There is a lack of research that examines earthworms in reduced tillage systems that include potato or sugar beet, particularly where soils are susceptible to compaction during harvest with heavy machinery.

Additionally, farming system can have a large influence on earthworms. Organic farming, where synthetic pesticides and fertilisers are prohibited, makes greater use of animal and green manures, diverse crop rotations, and mechanical weeding (Gomiero et al., 2011). Hole et al. (2005) reviews studies where earthworms are both positively and negatively affected by organic farming. Most studies of earthworms in organic arable farming have been limited to short duration experiments that compared fields without proper experimental design to account for spatial variability in soil properties (Irmler, 2010).

Recent studies have investigated arable soil tillage effects on earthworms (Capowiez et al., 2009; De Oliveira et al., 2012; Ernst and Emmerling, 2009; Peigné et al., 2009). However, an extensive literature search revealed few studies that have assessed the effects of tillage systems on earthworms over short- and medium- timescales simultaneously in both conventional and organic farming systems.

The objective of this study was to quantify the effects of tillage systems on earthworm populations in conventional and organic farming. It was hypothesised that mouldboard ploughing reduces earthworm populations immediately following ploughing (epigeic and anecic species in particular) in both conventional and organic farming and that this decrease would continue for several weeks relative to the reduced tillage treatment. Over the medium term (4 years), it was hypothesised that reduced tillage intensity systems increase earthworm populations relative to mouldboard ploughing in both conventional and organic farming (epigeic and anecic species in particular). Furthermore, earthworm species abundances were expected to be positively correlated with soil organic matter content and soil moisture but negatively correlated to soil compaction.

2.2. MATERIALS AND METHODS

2.2.1. SITE CHARACTERISTICS

The study was conducted at the PPO Lelystad experimental farm of Applied Plant Research Wageningen UR, in the Netherlands, in a polder reclaimed in 1957 (52° 31'N, 5° 29'E). The daily mean temperature ranged from 2° C in winter to 17° C in summer months, and mean rainfall was 794 mm per year during the study (Royal Netherlands Meteorological Institute, 2013). The soil type is a calcareous marine clay loam with 23% clay, 12% silt, and 66% sand. Soil pH is 7.9, and soil organic matter is 3.2% averaged across fields at the experimental farm.

2.2.2. EXPERIMENTAL DESIGN

Soil tillage treatments were sampled in two parallel field experiments (conventional and organic farming) in this study (Figure 2.1). Conventional and organic farming systems had unique crop rotations with individual fields at a different phase of their rotation (Table 2.1). Rotations contained mainly root and cereal crops, although grass and cabbage were also included in organic farming. Cover crops were grown during fallow periods when feasible. Conventional fields received yearly synthetic fertiliser applications and were treated bi-weekly with herbicides during the growing season. Organic fields received yearly cow manure (solid or slurry) applications of 20-40 Mg ha^{-1} yr^{-1}. Organic field A in autumn 2010 did not receive manure because of the reduced nitrogen required by the following leguminous crop (wheat/faba). Tillage treatments received the same amounts of fertilisers and herbicides in conventional fields, or manure in organic fields. Organic fields received certification in 2004 and no synthetic fertilisers or pesticides have been used since 2002.

Sampling was conducted in two fields under conventional and two fields under organic farming. Each field contained 12 plots (3 tillage systems by 4 blocks) of 85 m by 12.6 m each, arranged in randomised complete blocks (Figure 2.1). Each plot contained 4 beds of 3.15 m along controlled-traffic lanes where all field operations, except harvest, were done. All plots were mouldboard ploughed annually previous to tillage system initiation in autumn 2008. Tillage systems were: (i) minimum tillage (MT) with optional subsoiling to 18–23 cm in autumn if soil compaction was high (based on visual assessment of soil pit and/or penetrometer readings) with cultivation to 8 cm for seedbed preparation, (ii) non-inversion tillage (NIT) with yearly sub-soiling to 18–20 cm in autumn and cultivation to 8 cm for seedbed preparation, (iii) mouldboard ploughing (MP) to 23–25 cm in autumn and cultivation to 8 cm for seedbed preparation. Sub-soiling in MT (done only in 2009 and 2010) and NIT plots was done using a Kongskilde Paragrubber Eco 3000.

A short-term study was conducted in conventional field B (Conv B) and organic field B (Org B), and medium-term earthworm monitoring was done in conventional field A (Conv A) and organic field A (Org A) (Figure 2.1, Table 2.1). Separate fields were used for

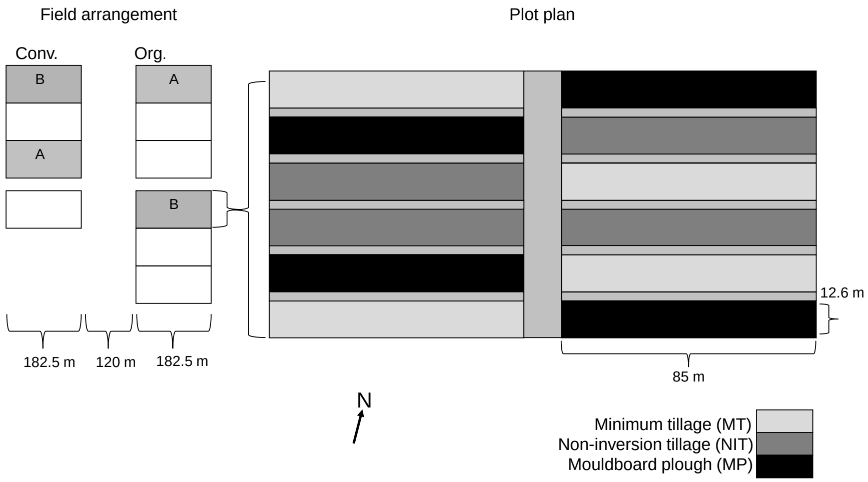

Figure 2.1: Arrangement of experimental fields (left) and plot plan (right)

the short- and medium-term studies to reduce disturbance due to sampling.

Table 2.1: Crop rotation per field (cover crop/green manure)[1]

Year\Field	Org A	Org B	Conv A	Conv B
2009	Spring wheat (white mustard)	Potato (grass clover)	Spring barley (rye grass)	Sugar beet
2010	Carrot (white clover)	Grass clover	Onion	Winter wheat
2011	Wheat/faba (white mustard)	Cabbage	Potato (rye grass)	Onion (yellow mustard in MT and NIT only)
2012	Potato	Spring wheat	Sugar beet	Potato

[1] Organic farming has a 6 year crop rotation. Only 4 years of the rotation are shown here.

2.2.3. DATA COLLECTION AND ANALYSES

SHORT-TERM STUDY

A sampling campaign was conducted during autumn 2011 to investigate the short-term effects of mouldboard ploughing on earthworm populations. Earthworms were sampled 15 days (d) before ploughing in MP and NIT plots of Conv B, then 5 d, 16 d, and 35 d after ploughing to assess effects over time. MP and NIT plots of Org B were sampled 3 d before ploughing then 2 d, 20 d, and 53 d, and 191 d (after seeding of spring wheat) after ploughing. NIT plots were sampled, as a reference, on the same dates as MP plots, to account for changes in earthworm populations resulting from changing environmental conditions with time. Conv B was non-inversion tilled on 28-Oct-2011, before initiation of the short-term study. Org B was not non-inversion tilled during autumn 2011. Three 20 x 20 x 20 cm monoliths were handsorted for earthworms from each plot according to Van Vliet and De Goede (2006). To extract anecic earthworms from below 20 cm, 500 ml of 0.185% formaldehyde solution was applied to the bottom of the pit. Since MT had been sub-soiled in 2009 and 2010 to reduce soil compaction, it was not sampled for the short-term study to avoid the redundancy of including two treatments (NIT + MT) that had been treated equally.

MEDIUM-TERM STUDY

To monitor medium-term effects of tillage systems on earthworm populations Conv A and Org A were sampled between 2009 and 2012 during spring and autumn seasons (excluding spring 2010). Earthworms were sampled as described in Section 2.2.3, after seeding in spring and again before ploughing in autumn. Soil moisture was measured at each earthworm sampling by taking composite soil samples (n=5, 20 mm diameter) to 20 cm depth immediately adjacent to each excavated monolith (data not shown). In addition, soil organic matter (SOM) content and soil penetration resistance (as a proxy for soil compaction) were measured during the autumn 2011 sampling. A randomised subsample of each soil monolith that had been handsorted for earthworms was taken for SOM analysis. Penetration resistance profiles (n=4) were taken in undisturbed soil within 20 cm of each monolith using a penetrologger (Eijkelkamp Agrisearch 2011, 1 cm^2 cone diameter 60°).

LABORATORY ANALYSES

Earthworm samples were stored, with a small amount of soil so earthworms would not dry out, at 4° C for a maximum of two days. Earthworms were cleaned with water and patted dry with tissue paper, after which they were counted, weighed (including gut contents) and fixed in 70% ethanol. Biomass was not measured in spring 2009. Adults were identified according to Sims and Gerard (1999) and juveniles with Stöp-Bowitz (1969) to species level. Where species level identification of juveniles was not possible individuals were grouped as either *Aporrectodea/Allolobophora* or *Lumbricus* juveniles. Soil moisture was determined gravimetrically by drying subsamples at 105° C for 24 hours. Soil organic matter content was determined by loss-on-ignition at 550° C (Normalisatie-Instituut, 1992).

STATISTICAL ANALYSES

Tillage system effects on earthworm species abundances, total earthworm abundance (adults + juveniles), total earthworm biomass, adult/juvenile ratio, species richness, and Shannon diversity index were investigated using linear mixed effects models with repeated measures. Fixed effects were tillage system and sampling date, and random effects were block and plot. Earthworm species abundances and total biomass were averaged per plot before statistical analysis. Species richness and Shannon diversity were calculated using species abundances averaged per plot. Farming systems (conventional or organic) were analysed separately. Fields under conventional and organic farming were separated spatially (Figure 2.1), and not inside of the randomised complete block design and could not be statistically tested. A squared-root transformation of earthworm species abundances, total earthworm abundance, and total earthworm biomass was used to fit ANOVA assumptions. Autoregressive correlation was used for repeated measures. Relations between earthworm and soil parameters across tillage and farming systems were explored by redundancy analysis (RDA) of autumn 2011 data. Earthworm species abundances, soil organic matter, soil moisture, and penetration resistance (averaged per plot (n=4) per 5 cm to 30 cm depth) were used as response variables to the explanatory variables farming systems (Conv and Org) and tillage systems (MP and NIT). Computations for linear mixed effects models (Pinheiro et al., 2012), multiple means comparisons (Lenth, 2012), RDA, and Shannon diversity (Kindt and Coe, 2005; Oksanen et al., 2012) were performed using R (R Core Team, 2012). The type I error rate (α) was set at 0.05 for all statistical tests, unless otherwise stated.

2.3. Results

2.3.1. Short-term study: effect of mouldboard ploughing on earthworm populations

Total earthworm abundance in conventional field B (Conv B) prior to ploughing in autumn 2011 was 512 m^{-2} in mouldboard ploughing (MP), about 20% higher than non-inversion tillage (NIT) (Table 2.2). Following ploughing, earthworm abundance was reduced by 66% after 5 days and a further 74% after 2 weeks, whereas in NIT earthworm abundance did not change with time. Earthworm biomass responded similarly. Mean adult/juvenile (A/J) ratio was 0.17. A total of 6 earthworm species were found in Conv B (Table 2.2). *Aporrectodea caliginosa* was 83%, *Aporrectodea rosea* was 10%, *Eiseniella tetraedra* was 5%, and *Lumbricus rubellus* 2% of earthworms. *Lumbricus castaneus* and *Lumbricus terrestris* were also found but were less than 1% of earthworms. *A. caliginosa* and *A. rosea* abundances were significantly reduced more than 6 fold after ploughing relative to pre-ploughing. Mean species richness was significantly reduced from 4 to about 2 after ploughing. Mean Shannon diversity was not significantly affected by tillage system or sampling date, but on average was 0.49 in NIT and 0.46 in MP (data not shown).

Total earthworm abundance in organic field B (Org B) prior to ploughing was 585 m^{-2} in MP, about 50% lower than NIT (Table 2.3). Three weeks after ploughing, total earthworm abundance was reduced by 85%. Total earthworm biomass however declined by more than 50% in both MP and NIT during the short-term experiment. Earthworm abundance and biomass recovered to pre-ploughing levels by spring 2012. A/J ratio was 0.17 in NIT before ploughing, significantly higher than MP, and by the 3rd sampling date declined slightly, to levels similar to MP. A total of 7 earthworm species were found in Org B (Table 2.3) in autumn 2011. *A. caliginosa* was 82%, *L. rubellus* was 13%, *E. tetraedra* was 2%, and *A. rosea* and *Allolobophora chlorotica* were 1% of earthworms. *L. terrestris* and *Lumbricus castaneus* were also present but less than 1% of earthworms. Mean species richness did not decrease following ploughing, and was significantly lower in MP (2.7) than in NIT (4.0). Mean Shannon diversity was not significantly affected by tillage system or sampling date, and was 0.64 in NIT and 0.42 in MP (data not shown), on average.

Table 2.2: Earthworm abundances and biomass before and after ploughing in Conv B.[1]

Tillage system	Sampling date (2011)	*Aporrectodea caliginosa* (m^{-2})	*Aporrectodea rosea* (m^{-2})	*Eiseniella tetraedra* (m^{-2})	*Lumbricus rubellus* (m^{-2})	Total abundance (m^{-2})	Biomass ($g\,m^{-2}$)	Adult/juvenile ratio [2]	Species richness
MP	1-Nov (MP - 15 d)	425 a	38 a	21	13 a	512 a	68 a	0.22	4.0 a
	21-Nov (MP + 5 d)	150 b	11 ab	3	0 b	175 b	25 b	0.36	2.0 b
	2-Dec(MP + 16 d)	36 c	1 b	1	2 ab	45 c	7 c	0.13	2.2 b
	21-Dec (MP + 35 d)	65 c	1 b	18	0 b	97 cb	8 c	0.25	1.7 b
NIT	1-Nov (MP - 15 d)	375 a	29 ab	0	3 *	420	41 *	0.11	2.2 *
	21-Nov (MP + 5 d)	345 ab *	47 ab *	3	2	406 *	46 *	0.13 *	2.7 * [3]
	2-Dec(MP + 16 d)	227 b *	56 a * [4]	4	1	301 *	28 *	0.08	3.0 * [5]
	21-Dec (MP + 35 d)	295 ab *	17 b *	9	2	344 *	36 *	0.06 *	3.0 *

[1] Species abundances, total abundance, and total biomass are back-transformed means. Tillage systems: non-inversion tillage (NIT) and mouldboard plough (MP). Species with > 1% of overall abundance are included, other species present were *Lumbricus terrestris* and *Lumbricus castaneus*. Species abundance columns are ordered from left to right by decreasing overall abundance. Letters indicate significant treatment differences within tillage system between sampling dates and '*' indicates significant differences between tillage systems within sampling date ($P < 0.05$). [2] $P = 0.05$ [3] $P = 0.08$ [4] $P = 0.06$ [5] $P = 0.08$

2

Table 2.3: Earthworm abundances and biomass before and after ploughing in Org B.[1]

Tillage system	Sampling date (2011)	*Aporrectodea caliginosa* (m^{-2})	*Lumbricus rubellus* (m^{-2})	*Eiseniella tetraedra* (m^{-2})	*Aporrectodea rosea* (m^{-2})	Total abundance (m^{-2})	Biomass ($g\,m^{-2}$)	Adult/juvenile ratio	Species richness
	26-Oct (MP - 3 d)	510 a	67 a	0 b	0 b	585 a	71 a	0.09	2.0 c
	31-Oct (MP + 2 d)	381 a	51 a	1 ab	0 b	446 a	35 b	0.04	2.5 bc
MP	18-Nov (MP + 20 d)	80 c	9 b	0 b	1 ab	94 c	16 b	0.04	2.0 c
	21-Dec (MP + 53 d)	204 b	7 c	1 b	4 ab	242 b	26 b	0.05	3.0 ab [2]
	7-May-2012 (MP + 191 d)	519 a	85 a	19 a	6 a	639 a	81 a	0.08	3.8 a
	26-Oct (MP - 3 d)	1023 *	178 *	14 ab *	5 b *	1243 *	120 ab *	0.17 a *	3.8 b * [3]
	31-Oct (MP + 2 d)	939 *	142 *	41 a *	1 b	1156 *	82 bc *	0.10 ab *	3.8 ab *
NIT	18-Nov (MP + 20 d)	737 *	125 *	15 ab *	31 a *	963 *	77 c *	0.09 b	4.8 a *
	21-Dec (MP + 53 d)	720 *	93 *	6 b	20 a *	876 *	64 c *	0.06 b	4.0 ab *
	7-May-2012 (MP + 191 d)	844 *	164 *	25 ab	10 ab	1065 *	119 a *	0.10 b [4]	3.8 ab

[1] Species abundances, total abundance, and total biomass are back-transformed means. Tillage systems: non-inversion tillage (NIT) and mouldboard plough (MP). Species with > 1% of overall abundance are included, other species present were *Allolobophora chlorotica*, *Lumbricus terrestris*, and *Lumbricus castaneus*. Species abundance columns are ordered from left to right by decreasing overall abundance. Letters indicate significant treatment differences within tillage system between sampling dates and '*' indicates significant differences between tillage systems within sampling date ($P < 0.05$). [2] $P = 0.09$ [3] $P = 0.06$ [4] $P = 0.06$

2

2.3.2. MEDIUM-TERM STUDY: EFFECT OF REDUCED TILLAGE SYSTEMS ON EARTHWORM POPULATIONS

In Conv A, total earthworm abundance was not significantly affected by tillage system at any sampling date. Mean total earthworm abundance was 153 m^{-2} and total earthworm biomass was 32 g m^{-2} for reduced tillage (minimum (MT) and NIT averaged), 15% higher than MP over the medium-term study across all sampling dates (Table 2.4). One or both reduced tillage systems had higher total earthworm biomass than MP at autumn 2009 ($P = 0.05$), spring 2011 ($P = 0.05$), and spring 2012 ($P = 0.07$). Mean A/J ratio was 0.64 in reduced tillage and 0.36 for MP. A total of 8 earthworm species were found in Conv A (Table 2.4). *A. caliginosa* was 86%, *A. rosea* was 7%, and *L. rubellus* 5% of earthworms. *L. castaneus*, *E. tetraedra*, *A. chlorotica*, *L. terrestris*, and *Aporrectodea limicola* were also found but were less than 1% of earthworms. Mean species richness in reduced tillage systems was 2.3, significantly higher than 1.7 in MP, and was significantly higher in one or both reduced tillage system than MP at 3 sampling dates. No significant effects of tillage system on Shannon diversity were found, however mean Shannon diversity was 0.4 in reduced tillage and 0.2 in MP (data not shown). *L. rubellus* was not present in MP at 5 out of 6 sampling dates and had significantly higher abundance in MT and/or NIT than MP at 3 sampling dates.

In Org A, at 3 of 6 sampling dates total earthworm abundance in MP was significantly higher than reduced tillage (M or NIT). Mean total earthworm abundance was 297 m^{-2} and total earthworm biomass was 52 g m^{-2} for reduced tillage, 45% and 15% lower than MP respectively across all sampling dates (Table 2.5). No significant tillage system effects were found for A/J ratio, however mean A/J ratio was 0.56 in reduced tillage and 0.45 in MP. A total of 9 earthworm species were found in Org A (Table 2.5). *A. caliginosa* was about 63%, *L. rubellus* 16%, *E. tetraedra* 16%, and *A. rosea* was 4% of earthworms. *A. chlorotica*, *L. castaneus*, *L. terrestris*, *Aporrectodea longa*, and *Murchieona minuscula* were also present but were less than 1% of earthworms. No significant tillage system effects on species richness or Shannon diversity were found. Mean species richness was 3.4 in reduced tillage and 3.5 in MP and mean Shannon diversity was 0.8 in reduced tillage and 0.7 in MP (data not shown). *A. caliginosa* had significantly higher abundance in MP than at least one of MT or NIT at all sampling dates.

Table 2.4: Earthworm abundances and biomass in Conv A.[1]

Sampling date	Tillage system	*Aporrectodea caliginosa* (m^{-2})	*Aporrectodea rosea* (m^{-2})	*Lumbricus rubellus* (m^{-2})	Total abundance (m^{-2})	Biomass ($g\,m^{-2}$)	Adult/juvenile ratio	Species richness
Spring 2009	MT	50	7	1	68	-	1.01 b	2.2 a
	NIT	26	2	2	38	-	2.37 a	1.7 ab
	MP	40	1	0	41	-	0.30 b	1.2 b
Autumn 2009	MT	101	4	0	110	15 ab	0.41	1.7 ab
	NIT	153	7	2	169	26 a[2]	0.14	2.5 a
	MP	87	4	0	95	11 b	0.14	1.5 b
Autumn 2010	MT	170 b	7	17 a	208	56	0.79	2.5
	NIT	277 a	38	22 a	358	77	0.37	3.0
	MP	240 ab	30	0 b	279	79	0.89	2.5
Spring 2011	MT	49	3	2	60	12 a[3]	0.63	2.0
	NIT	52	2	0	61	8 ab	0.50	2.0
	MP	23	3	0	29	3 b	0.25	1.5
Autumn 2011	MT	218 a	2	12 a	245	44 a[4]	0.48	2.8
	NIT	113 b	3	0 b	127	25 b	0.49	2.0
	MP	181 ab	10	0 b	192	26 ab	0.16	2.0
Spring 2012	MT	154	2	29 a	188	24 ab	0.24	2.5 a
	NIT	176	7	17 a	204	35 a[5]	0.19	2.8 a
	MP	136	1	1 b	143	18 b	0.36	1.5 b

[1] Species abundances, total abundance, and total biomass are back-transformed means. Tillage systems: minimum (MT), mouldboard plough (MP), and non-inversion tillage (NIT). Species with > 1% of overall abundance are included, other species present were *Lumbricus terrestris*, *Lumbricus castaneus*, and *Eiseniella tetraedra*. Species abundance columns are ordered from left to right by decreasing overall abundance. Letters indicate significant differences between tillage systems within sampling date ($P < 0.05$). [2] $P = 0.05$ [3] $P = 0.05$ [4] $P = 0.07$ [5] $P = 0.07$

2

Table 2.5: Earthworm abundances and biomass in Org A.[1]

Sampling date	Tillage system	*Aporrectodea caliginosa* (m^{-2})	*Lumbricus rubellus* (m^{-2})	*Eiseniella tetraedra* (m^{-2})	*Aporrectodea rosea* (m^{-2})	Total abundance (m^{-2})	Biomass ($g\,m^{-2}$)	Adult/juvenile ratio	Species richness
Spring 2009	MT	125 b	45	6	8	195 b	-	0.41	4.3
	NIT	147 b	31	15	17	236 ab	-	0.26	3.8
	MP	273 a	45	21	5	375 a	-	0.42	3.3
Autumn 2009	MT	227 b [2]	168	0	9	415	129 a	0.46	3.0
	NIT	151 b	116	1	5	289	82 b	0.36	3.5
	MP	271 a	80	2	16	389	78 b	0.24	4.0
Autumn 2010	MT	89 b	52	1	10	159 b	40 b	0.61	3.0
	NIT	64 b	15	1	5	104 b	34 b	0.57	2.8
	MP	271 a	44	7	23	357 a	75 a	0.35	3.8
Spring 2011	MT	18 ab	4	1	1	28	11	2.00	2.0
	NIT	8 b	5	1	1	21	6	0.25	2.5
	MP	58 a	2	1	2	75	16	1.22	2.2
Autumn 2011	MT	365 b	50	121	10	560 b	97	0.38	3.8
	NIT	293 b	51	185	6	555 b	84	0.42	3.5
	MP	566 a	44	188	31	841 a	93	0.19	4.0
Spring 2012	MT	309 ab	84	120	12	557	74 a	0.50	4.2
	NIT	230 b	80	111	9	446	58 ab	0.51	4.0
	MP	383 a	38	108	5	543	35 b	0.26	3.8

[1] Species abundances, total abundance, and total biomass are back-transformed means. Tillage systems: minimum (MT), mouldboard plough (MP), and non-inversion tillage (NIT). Species with > 1% of overall abundance are included, other species present were *Lumbricus terrestris*, *Lumbricus castaneus*, *Aporrectodea longa*, *Allolobophora chlorotica*, *Murchieona minuscula* and *Aporrectodea/Allolobophora* or *Lumbricus* juveniles. Species abundance columns are ordered from left to right by decreasing overall abundance. Letters indicate significant differences between tillage systems within sampling date ($P < 0.05$). [2] $P = 0.07$

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2.3.3. RELATIONS BETWEEN EARTHWORMS, MANAGEMENT, AND SOIL PROPERTIES

Soil property data used in the RDA are presented in Table 2.6. RDA eigenvalues indicated that 44% of total variance within earthworm and soil parameters measured in autumn 2011 were explained by the 1^{st} and 2^{nd} axes of the ordination diagram (Table 2.7, Figure 2.2). Both tillage and farming system explained significant proportions of total variance (Permutation test, $P < 0.01$). The 1^{st} axis separates farming systems (Org A on left and Conv A on right) (Figure 2.2). Furthermore, the 2^{nd} axis separates tillage within the Conv system, whereas there is overlap in Org. *L. rubellus* and *E. tetraedra* were more abundant in Org NIT than Conv MP and Conv NIT. Org NIT had higher soil organic matter, and *L. rubellus* and *E. tetraedra* abundances, which were positively correlated. Penetration resistance, at all depths, was highest in Conv NIT.

Table 2.6: Soil property data used in RDA.[1]

Farming system	Tillage system	Soil organic matter ($g\,kg^{-2}$)	Soil moisture ($g\,kg^{-2}$)	Penetration resistance (MPa)					
				0-5 *cm*	5-10 *cm*	10-15 *cm*	15-20 *cm*	20-25 *cm*	25-30 *cm*
Conv	NIT	31.3 a	203 b	0.5	1.2 a	1.9 a	2.2 a	1.9 a	1.9 a
	MP	29.4 b	219 a	0.4	0.8 b	1.1 b	1.2 b	1.0 b	1.2 b
Org	NIT	33.4 a	235	0.4	0.5	0.6 b	0.9	1.1	1.1
	MP	32.2 b [2]	217	0.4	0.5	0.7 a [3]	0.9	1.0	1.2

[1] Soil property data were measured simultaneously with earthworms in autumn 2011. Tillage systems: non-inversion tillage (NIT) and mouldboard plough (MP). Letters indicate significant treatment differences within farming system ($P < 0.05$). Soil organic matter and soil moisture were measured to 20 cm. [2] $P = 0.06$ [3] $P = 0.07$

Table 2.7: Results of redundancy analysis and permutation test for autumn 2011 earthworm and soil data

Ordination axis	Axis 1	Axis 2
Eigenvalues	5.92	1.11
Cumulative proportion of total variance explained	0.37	0.44
Species-environment correlations	0.91	0.69
Permutation significance test		
	F-ratio	P-value
Farming system	28.36	0.005
Tillage system	6.91	0.005

2.4. DISCUSSION

2.4.1. SHORT-TERM EFFECTS OF PLOUGHING ON EARTHWORMS

Mouldboard ploughing was shown to consistently reduce total earthworm abundance in the short term (up to 53 days). As hypothesised, earthworm abundance decreased immediately after ploughing and continued to decrease at subsequent samplings in both conventional and organic farming. This decrease may indicate that both direct (e.g., physical damage, predation) and indirect (e.g., food re-distribution) mechanisms may play a role (Curry, 2004). Ploughing and intensive tillage have been found to reduce earthworm populations over the short term (Boström, 1995; Curry et al., 2002; De Oliveira

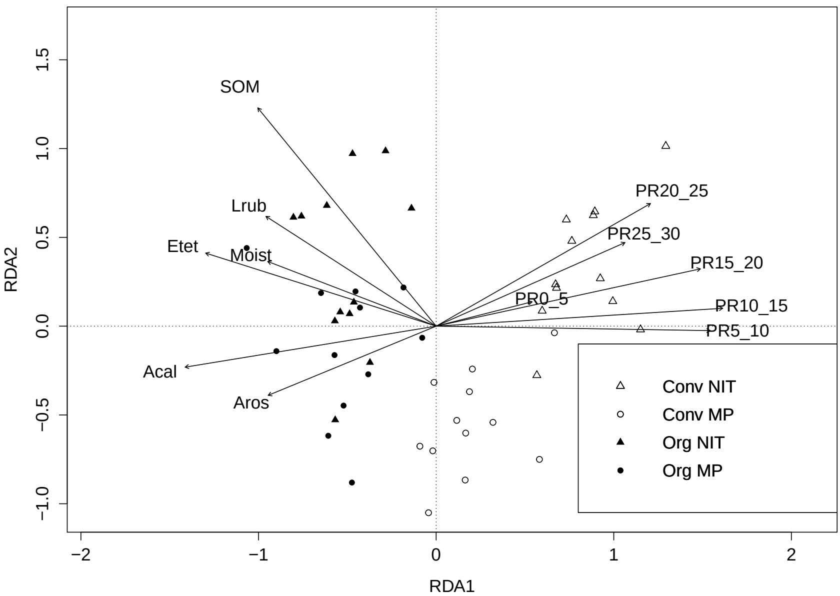

Figure 2.2: RDA triplot of earthworm and soil properties from autumn 2011. Symmetric scaling was used. Explanatory variables were tillage (mouldboard ploughing (MP) or non-inversion tillage (NIT)) and farming system (conventional (Conv) or organic (Org)). Response variables were earthworm species abundances (*Aporrectodea caliginosa* (Acal), *Lumbricus rubellus* (Lrub), *Eiseniella tetraedra* (Etet), and *Aporrectodea rosea* (Aros)), soil organic matter (SOM), penetration resistance (PR) by depth (cm), and soil moisture (Moist) measured at time of earthworm sampling.

et al., 2012). *Lumbricus rubellus* populations were affected by mouldboard ploughing similarly to other species. Anecic species abundances in the short-term study were too low (<1% of earthworms) to ascertain mouldboard ploughing effects.

In Org B, *A. caliginosa* abundance began to recover by 53 d after ploughing. Similarly, De Oliveira et al. (2012) found a mean increase of *A. caliginosa* of 141 m^{-2} in a 7 day period, after ploughing. Schmidt and Curry (2001) reported an increase of 125 m^{-2} following an initial decrease after ploughing in November and December 1995. There was a significant increase of 124 m^{-2} *A. caliginosa* and 8.47 g m^{-2} (assuming 84.7% of total biomass is *A. caliginosa* since *A. caliginosa* is 84.7% of total abundance) in 33 days (Table 2.3, Org B, MP 18-Nov to 21-Dec). This increase can be justified by earthworm population growth, assuming sufficient cocoon presence and a Q_{10} of 2, according to Boyle (1990) cited in Curry (2004). However, it should be noted that the decrease and subsequent increase in earthworm populations following mouldboard ploughing cannot be attributed to the ploughing effect itself with absolute certainty and may partly be an artefact of the sampling method. Ploughing may have caused displacement of earthworms below 20 cm depth, and the formaldehyde extraction below 20 cm depth may be less effective in recently ploughed, unconsolidated soil.

Earthworms can recover by the following season, as seen in both the short- and medium-term studies shown in Table 2.3 and Table 2.5. Boström (1995) attributed earthworm recovery to cocoon production and redistribution of organic matter through the plough layer making the food source more available for endogeics. Curry (2004) also suggests that soil inversion may increase organic matter availability to endogeic earthworms and that short-term factors such as predation may not play a role over the medium term.

In Org B pre-ploughing earthworm total abundance was two times higher in non-inversion tillage (NIT) than mouldboard ploughing (MP), in contrast to Conv B. Mouldboard ploughing clearly affected total earthworm abundance in Conv B and Org B. Conv B and Org B differed in that *Aporrectodea rosea* was second-most abundant and *L. rubellus* least abundant in Conv B, whereas the reverse was true in Org B. Manure additions (Peigné et al., 2009) and more diverse crop rotations (including legumes as ley) (Metzke et al., 2007; Peigné et al., 2009; Riley et al., 2008) may account for the differences in earthworm assemblages between farming systems. Therefore, as hypothesised, ploughing reduced total earthworm abundance and total earthworm biomass over the short term in Conv B. However, in Org B the hypothesis is confirmed for total earthworm abundance but not total earthworm biomass. In Org B ploughing reduced total earthworm abundance, however total earthworm biomass decreased in both MP and NIT. Contrary to expectations, Shannon diversity was not affected by ploughing over the short term. Species richness did decrease after ploughing in Conv B, although this could be due to rarefaction (Sanders, 1968).

2.4.2. MEDIUM-TERM EFFECTS OF REDUCED TILLAGE ON EARTHWORMS

Reduced tillage in the conventional farming system resulted in higher earthworm total biomass and *L. rubellus* (epigeic) in the medium-term study (4 years) as hypothesised. Contrastingly, reduced tillage in the organic farming system decreased total earthworm abundance driven by consistently lower endogeic *A. caliginosa* abundances. However, total earthworm biomass in MT was higher than MP at sampling dates with no total earthworm abundance effect (autumn 2009 and spring 2012), which may have been caused by a higher, if not significant, percentage of adults. *L. rubellus* abundances did not increase from reduced tillage in organic farming. Anecic species abundances were too low throughout the experiment, in all cases, to be able to draw meaningful conclusions on tillage effects.

Endogeics, in particular *A. caliginosa*, dominated all farming and tillage systems, as was also noted by Marinissen (1992) at a nearby location. *A. caliginosa* was also the most abundant species in the arable soils studied by Nuutinen (1992), Emmerling (2001), Bithell et al. (2005), and De Oliveira et al. (2012). *A. caliginosa* was the most abundant earthworm species in the medium-term study in both Conv A and Org A, as was also noted in Conv B and Org B in the short-term study. *A. rosea* was second most abundant in Conv A and last in Org A, and *L. rubellus* was second in Org A and third in Conv A. Hence, the relative abundances of the more numerous species show a consistent pattern.

It has been suggested that incorporation of organic matter during ploughing gives an advantage to endogeic species by increasing food availability (Chan, 2001; Ernst and Emmerling, 2009; van Capelle et al., 2012). Cropping and tillage systems that compact soils have a negative impact on earthworms (Capowiez et al., 2009; Wyss and Glasstetter, 1992). Marinissen (1992) noted that sugar beet harvest, a crop also in the current study (Table 2.1), under wet conditions resulted in high adult *L. rubellus* mortality, at one of their sampling dates. Soil organic matter was likely increased by the application of manure to organic farming fields. Incorporation of manure and crop residues by mouldboard ploughing likely resulted in the higher total earthworm abundances in MP than in one or both of the reduced tillage systems at 3 sampling dates. Higher total earthworm abundances in MP were driven by higher *A. caliginosa* in MP. Lacking this organic matter addition, reduced tillage in Conv A increased earthworm total biomass and benefited the epigeic species *L. rubellus* by leaving crop residues on the soil surface. Therefore, interactions between tillage system and organic matter management are important in explaining earthworm ecological group responses.

The earthworm community found in this study was similar to others in north western Europe (De Oliveira et al., 2012; Ernst and Emmerling, 2009; Nieminen et al., 2011; Valckx et al., 2009). *E. tetraedra* was more abundant than in other studies perhaps because of its affinity for moist conditions (Sims and Gerard, 1999), however *E. tetraedra* has been found previously in this polder (Faber and Hout, 2009; Van der Werff et al., 1998) and so its presence is not surprising. Earthworm communities in arable land are often dominated by endogeic species with low amounts of anecics, especially when under intensive tillage systems (De Oliveira et al., 2012; Ernst and Emmerling, 2009). In the current study, anecic earthworm abundances were negligible, which may be caused by a history of continuous mouldboard ploughing (Chan, 2001; Ernst and Emmerling, 2009; van Capelle et al., 2012) or from soil disturbance during potato harvesting (Curry et al., 2002). Neither earthworm abundance, biomass, species richness, nor Shannon diversity showed clear increase over the course of the medium-term study, indicating a lack of cumulative tillage system effect after 4 years.

Differences in earthworm dominance, abundance, and biomass were consistent between farming systems and between tillage systems over 4 years despite crop rotation and climatic factors having strong effects on absolute earthworm abundance and biomass at individual sampling dates. Position in the crop rotation may explain differing tillage system effects between Org B and Org A. In Org A MP had consistently higher earthworm abundances, whereas in Org B NIT had higher earthworm abundances. Higher earthworm abundances in Org B NIT may be due to organic matter inputs from grass clover clippings left on the soil surface during 2011 (Table 2.1), indicating that crop rotation plays an important role in earthworm population change.

2.4.3. Relations between earthworms and soil properties

Redundancy analysis (RDA) showed clear distinctions between tillage systems and farming systems. Pulleman et al. (2003) also found higher soil organic matter (SOM) and earthworm activity under organic farming in a similar soil type in the south west of the Netherlands. The review by Hole et al. (2005) suggests organic amendments in organic farming systems improve soil organic matter and increase earthworm abundance. Organic farming has been reported to have higher earthworm abundance (Hole et al., 2005; Kragten et al., 2010; Pfiffner and Mäder, 1997) and species richness (Flohre et al., 2011; Pfiffner and Mäder, 1997) than conventional farming. Contrastingly, Pelosi et al. (2009) found earthworm abundance, biomass and diversity to be the same in conventional and organic farming over their 3 year study on arable soils in France.

Hypotheses regarding earthworms and soil properties are partially confirmed in the current study. Redundancy analysis showed positive correlations of SOM and soil moisture at the time of sampling with *L. rubellus* and *E. tetraedra*, but only weak correlation with *A. caliginosa* and *A. rosea*. Ernst and Emmerling (2009), also using RDA, found that endogeics benefit from SOM in ploughed systems, which agrees with current findings for *A. caliginosa* and *A. rosea*. Soil compaction, represented by penetration resistance, was negatively correlated with *A. caliginosa* and *A. rosea* but not correlated to *L. rubellus*, *E. tetraedra* or soil moisture. Other studies have also found that reduced tillage compacts soil and negatively impact earthworms, particularly endogeics (Capowiez et al., 2012; Langmaack et al., 1999; Wyss and Glasstetter, 1992).

2.5. Conclusions

In the short term, mouldboard ploughing (MP) negatively affected earthworm abundances (up to 53 days), however they recovered to pre-ploughing levels by the following spring. This fast earthworm population recovery was also reflected in the medium-term study as shown by the general lack of negative MP effects on earthworm abundances. Total earthworm abundances in organic farming tended to be lower in reduced tillage than MP systems driven by the predominant species *Aporrectodea caliginosa*, whereas, reduced tillage positively affected the epigeic *Lumbricus rubellus* in conventional farming. Interactions between tillage and organic matter management probably explain differing responses of earthworm ecological groups in the two farming systems. In general, organic farming had higher earthworm abundances, biomass, and Shannon diversity than conventional farming. Variation between sampling dates was large, likely due to effects of crop and climatic conditions. Despite this variation consistent tillage system effects were observed on certain species.

Future work should clarify the interaction of tillage systems, crop rotation, and organic matter management on earthworm populations, in particular anecic species. Long-term studies should monitor earthworm diversity in relation to biophysical properties and how these affect the development of soil functioning.

3

EARTHWORM ASSEMBLAGES AS AFFECTED BY FIELD MARGIN STRIPS AND TILLAGE INTENSITY: AN ON-FARM APPROACH

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earthworm
soil
species
margin
tillage
abundances
arable
FM
NIT
strips
MP
earthworms
abundance
lumbricus
sampling
higher
biomass
rubellus
aporrectodea
non-inversion
mouldboard
farms
adjacent
ploughing
crop
properties
organic
autumn
caliginosa
moisture
experiment
terrestris
management
samplings
analysis
total
farm
variance
study
matter
significantly
systems
richness
figure

Earthworm species contribute to soil ecosystem functions in varying ways. Important soil functions like structural maintenance and nutrient cycling are affected by earthworms, thus it is essential to understand how arable farm management influences earthworm species. One aim of arable field margin strips and non-inversion tillage is to enhance agrobiodiversity, however their influence on earthworm species assemblages remains unclear. In particular, on-farm studies conducted over multiple years that capture variability across the landscape are rare. The current study monitored earthworm species assemblages on 4 farms in Hoeksche Waard, The Netherlands, from 2010 to 2012. It was hypothesised that arable field margin strips (FM) and non-inversion tillage (NIT; a reduced tillage system that loosens subsoil at 30 – 35 *cm depth) would have higher earthworm species abundances (epigeics and anecics in particular), soil organic matter, and soil moisture than adjacent mouldboard ploughing (MP) fields, and that earthworm numbers would decrease with distance away from FM into arable fields (MP only). FM contained a mean total earthworm abundance of* 284 m^{-2} *and biomass of* 84 g m^{-2} *whereas adjacent MP arable fields had only* 164 *earthworms* m^{-2} *and* 31 g m^{-2}*. Aporrectodea rosea, Lumbricus rubellus, Lumbricus terrestris, and Lumbricus castaneus were significantly more abundant in FM than adjacent arable soil under MP. However, no decreasing trend with distance from FM was observed in earthworm species abundances. A tillage experiment initiated on the farms with FM showed that relative to MP, NIT significantly increased mean total earthworm abundance by 34% to* 275 m^{-2} *and mean total earthworm biomass by 15% to* 51 g m^{-2} *over all sampling dates and farms. Lumbricus rubellus, Aporrectodea rosea, and Lumbricus terrestris were significantly more abundant overall in NIT than MP. FM and NIT positively affected earthworm species richness and abundances and it is noteworthy that these effects could be observed despite variation in environmental conditions and soil properties between samplings, farms, and crops. Higher top-soil organic matter and less physical disturbance in FM and NIT likely contributed to higher earthworm species richness and abundances. The anecic species Lumbricus terrestris (linked to water infiltration and organic matter incorporation) was more abundant in FM, but densities remained very low in arable soil, irrespective of tillage system.*

3

3.1. INTRODUCTION

Functional agrobiodiversity (FAB) programs are being implemented to reverse negative impacts of agricultural land-use intensification. Practises such as non-crop areas (i.e., field margin strips), reduced tillage, and crop diversification aim to promote above and/or below-ground biodiversity and function (Bianchi et al., 2013). Earthworms play important roles in soil nutrient and organic matter dynamics, and soil structure formation (Edwards, 2004) and are strongly affected by soil pH, organic matter, and soil moisture (Curry, 2004). Arable cropping and soil tillage affect earthworms through mechanical damage, reduction and vertical redistribution of organic matter, changes in soil water regime, and habitat disruption (Curry, 2004; Hendrix et al., 1992; Lee, 1985; van Capelle et al., 2012). Ecological groups of earthworms (Bouché, 1977) play important roles in determining certain soil functions (Keith and Robinson, 2012). Epigeic earthworms live and feed at the soil surface and contribute to organic matter incorporation and decomposition, anecic earthworms also feed at the soil surface but create deep vertical burrows and are considered most important for continuous soil pore formation and water infiltration (Keith and Robinson, 2012; Sims and Gerard, 1999). Endogeic earthworms affect soil porosity and aggregate stability by feeding in the upper mineral soil layers (Keith and Robinson, 2012; Sims and Gerard, 1999). However, farm management effects on total earthworm numbers have often been studied without acknowledgement of changes in species composition (Spurgeon et al., 2013).

Field margin strips are border areas of arable fields that can contain grass/herb mixtures with flowering species to encourage above-ground biodiversity and natural enemies of crop pests (Dennis and Fry, 1992; Marshall, 2004) and may be implemented as part of FAB programs (Bianchi et al., 2013) and agri-environmental schemes (Musters et al., 2009). Field margin strips have also been created as buffer strips to reduce surface water contamination and enhance landscape aesthetics (Bianchi et al., 2013). It has been proposed that grassy field margin strips along arable fields can contribute to higher soil macrofaunal diversity and provide source populations for species, including earthworms, that can colonise arable fields (Lagerlöf et al., 2002; Smith et al., 2008). Studies have shown higher earthworm numbers and diversity in grassy field margin strips compared to adjacent arable soil (Hof and Bright, 2010; Smith et al., 2008), however field margin strips have also been shown to contain lower earthworm numbers than adjacent arable fields (Lagerlöf et al., 2002). Therefore, effects of grassy field margins on earthworm species assemblages require clarification.

Reduced tillage systems that improve soil structure (e.g., aggregate stability, friability and shear strength) (Carter, 1992; Munkholm et al., 2001) and reduce farming costs (Morris et al., 2010) continue to gain attention in The Netherlands and other parts of Europe. Contrasting results have been reported for effects of tillage systems on earthworms, probably due to large variation in reduced tillage practices and implements, and due to lack of attention for differing responses among earthworm species (Chan, 2001). In particular, non-inversion tillage, a reduced tillage system without soil inversion by ploughing but still a relatively intense cultivation, may benefit earthworms, especially epigeics and anecics, by decreasing the intensity of soil disturbance while leaving an increased proportion of crop residues at the soil surface (Chan, 2001; Curry, 2004; Ernst and Emmerling, 2009; Morris et al., 2010). On the other hand, ploughing may give advantage to endogeic species (e.g., *Aporrectodea caliginosa*) because of increased access to food after incorporation of crop residues (Chan, 2001; van Capelle et al., 2012).

Influences of field margin strips and non-inversion tillage on earthworm assemblages in field studies should be conducted at multiple on-farm locations to capture spatial heterogeneity across the landscape and to verify patterns observed at single field research stations (e.g., (Curry et al., 2002; Ernst and Emmerling, 2009; Marinissen, 1992)). Moreover, it is important that earthworm samplings take place over multiple seasons and years to encompass temporal variability (Pulleman et al., 2012; Roarty and Schmidt, 2013). The objective of the current study was to quantify the effects of field margin strips and reduced tillage on earthworms species assemblages for multiple farms and cropping seasons. Arable field margin strips were expected to contain higher earthworm numbers than adjacent arable land (i.e., total abundance and total biomass, epigeic and anecic species abundances, and adult/juvenile ratio). These earthworm parameters were expected to decrease with distance from field margin strips. In addition, non-inversion tillage would result in higher earthworm parameters compared to mouldboard ploughing. Lastly, higher earthworm species abundances (epigeic and anecic species in particular) in FM and NIT were expected to coincide with increased topsoil soil organic matter and soil moisture at the time of sampling compared to MP (due to crop residues left at the soil surface to a greater extent, longer cover crop presence, and less soil disturbance compared to MP).

3.2. MATERIALS AND METHODS

3.2.1. STUDY AREA

The study was conducted in Hoeksche Waard, The Netherlands. The region is a 325 km^{-2} island consisting of polders that were gradually reclaimed from the sea starting in the 15th century. Currently, Hoeksche Waard is mainly under arable land use with crop rotations that include potato, sugar beet, and winter wheat among other cereal and horticultural crops (Rutgers et al., 2012; Steingröver et al., 2010). A functional agrobiodiversity (FAB) program began in 2004 on farms where field margin strips were created to promote natural crop pest enemies (Bianchi et al., 2013; Steingröver et al., 2010). Daily mean temperature is 10°C and annual precipitation is 900 mm (Royal Netherlands Meteorological Institute, 2013). Soils are hydromorphic calcareous sandy loam to clay (de Bakker et al., 1989), formed in marine deposits that, in general, overlay more sandy layers (below 45 – 60 cm) (Alterra, 2013). Mean high groundwater depths are 45 – 60 cm and mean low depths are 140 – 170 cm (Alterra, 2013).

3.2.2. EXPERIMENTAL DESIGN

Earthworms were sampled on 3 private farms in the eastern part of Hoeksche Waard and at PPO Westmaas research farm of Wageningen University and Research Centre, all within a 10 km radius of each other. Sampling was done during spring 2010, autumn 2010, autumn 2011, and spring 2012.

Transects (n=4) were set up within fields neighbouring field margin strips (FM) to test the effects of distance from FM on earthworm species abundances. Sampling along the transects consisted of 4 sample locations in grassy field margin strips, and 4 at 0.5 m, 30 m, and 60 m from field margin edges in each mouldboard ploughed field. Earthworm samples at each distance were spaced 8 m apart laterally (Figure 3.1).

An additional aspect of land management was investigated at each farm by using a Tillage Experiment set up in 2008 that consisted of non-inversion tillage (NIT) plots within pre-existing conventional mouldboard ploughing fields (n=4). Sampling locations in NIT plots were paired with adjacent locations in MP fields. At least a 2 m buffer was maintained between the outermost sampling locations and plot edges. In each tillage pair (n=4) a total of 8 earthworm samples were taken per plot per sampling date. The sampling scheme consisted of 4 sample locations spaced 8 m apart at 30 m and 4 sample locations at 60 m from field edges (Figure 3.1). Only 3 of 4 farms had complete tillage system pairs at the autumn 2011 and spring 2012 samplings.

Simultaneous sampling of earthworms and soil properties in the FM and Tillage Experiments allowed for data to be combined and inferences to be drawn on the influences of land management on soil properties and correlations with earthworm species abundances.

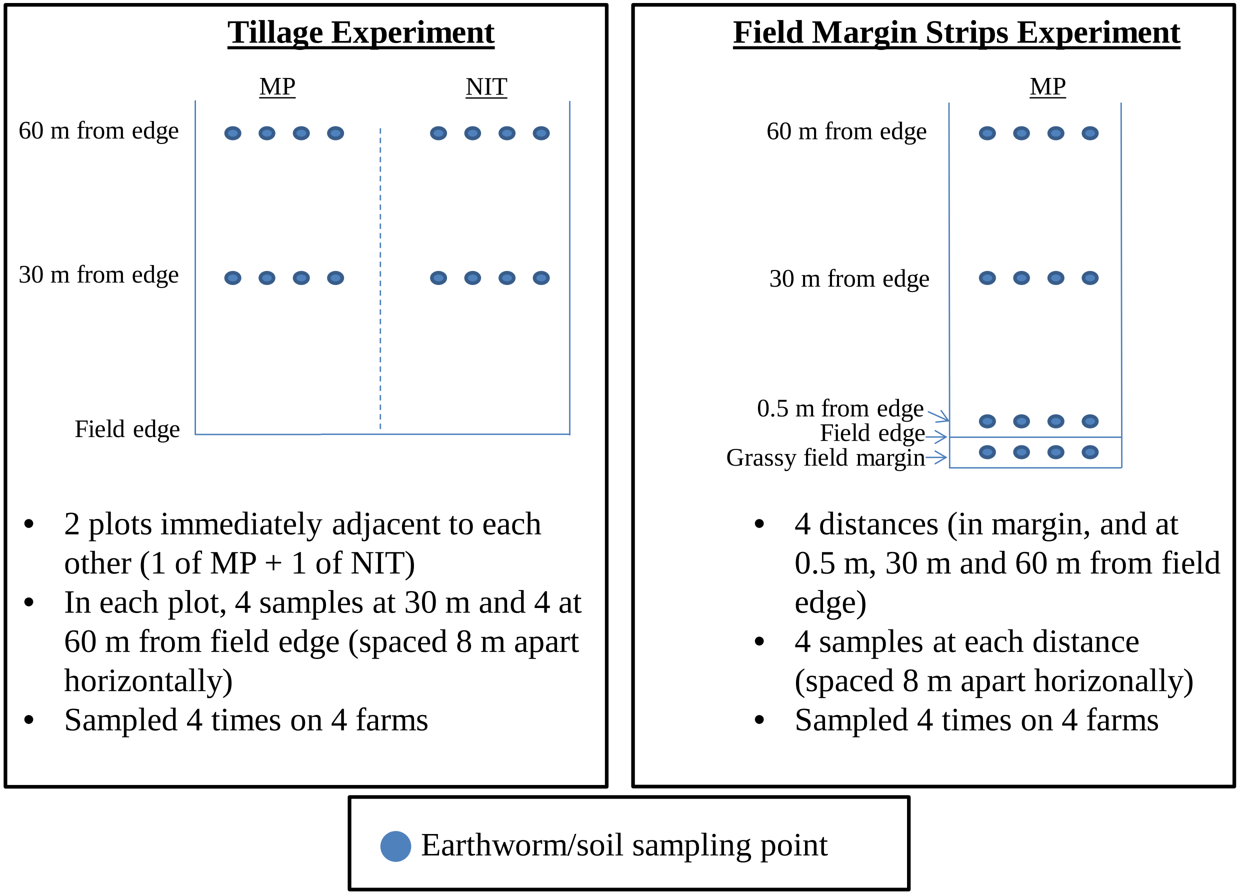

Figure 3.1: Experimental design. Arrangement of earthworm and soil sampling points used in the Tillage Experiment (left) and in the arable Field Margin Strips Experiment (right)

3.2.3. FARM MANAGEMENT

In the FM Experiment permanent FM were established between 2001 and 2005. Strips (3–4 m wide) located between ditches and arable fields were seeded with grass or grass/herb mixtures. FM were mown 1-2 times per year. Cuttings from FM were left in the strips on two farms, and were removed on the other two. FM were driven upon incidentally during ditch cleaning and other occasions. Neither fertilisers nor agrochemicals were applied to the strips.

In the Tillage Experiment both tillage systems contained a set of distinct practises which were uniform across farms. The principle difference between tillage systems is the primary tillage instrument (mouldboard ploughing (MP) or non-inversion tillage (NIT)). MP was done every autumn to 25 – 30 cm depth (in the FM and Tillage experiment). NIT was characterised by use of the Kongskilde Paragrubber Eco 3000 (or chisel plough in some cases) to 30 – 35 cm to replace the mouldboard plough as primary tillage instrument so that soil was loosened at depth (about 50% of subsoil volume directly affected by tines) and not inverted during tillage. Cover crops and crop residues were managed differently in NIT and MP due to the difference in primary tillage. Cover crops and crop residues are left at the soil surface and not incorporated into the soil in NIT due to the absence of mouldboard ploughing. In the MP system cover crops and crop residues are ploughed under in autumn and soil is left bare until spring. Cover crops are therefore maintained as a live mulch at the soil surface for longer in NIT than in the standard MP practise in The Netherlands. Crop residues were retained (except for wheat straw in some cases) and superficially incorporated in NIT before seeding of the next crop and ploughed under in autumn in MP.

All farms used synthetic fertilisers and chemical pesticides according to normal practises in the area, which were applied in equal quantities to MP and NIT. Pig or cow slurry was applied in/after cereal crops and sometimes sugar beet at 15 – 50 $t\,ha^{-1}$ on all farms except Westmaas.

Crop rotations included cereals and tuber crops. Crop rotations in FM Experiment are given in Table 3.1 and in the Tillage Experiment are given in Table 3.2. Crop residues were left on the soil surface after harvest in general, but wheat straw (not stubble) was sometimes removed on some farms. Cover crops were used in most years (Tables 3.1 and 3.2). A superficial tillage operation using a harrow (7 – 10 cm depth) to prepare the seedbed is done in spring for the main crop and following harvest in autumn for the cover crop.

Table 3.1: Crop rotations in Field Margin Strips Experiment [1]

	Farm 1	Farm 2	Farm 3	PPO Westmaas
2009	Winter wheat (Radish)	Potato	Sugar beet	Winter wheat (Radish)
2010	Sugar beet	Winter wheat	Winter wheat	Sugar beet
2011	Winter wheat (Italian ryegrass)	Onion	Pea	Winter wheat (Radish)
2012	Potato	Sugar beet	Potato	Potato

[1] Cover crops are indicated within parentheses.

Table 3.2: Crop rotations in Tillage Experiment [1]

	Farm 1	Farm 2	Farm 3	PPO Westmaas
2009	Brussels sprouts	Winter wheat (Radish)	Winter wheat	Winter wheat (Radish)
2010	Winter wheat (Italian ryegrass)	Winter wheat (Mustard)	Pea (Vetch + Black oat)	Sugar beet
2011	Potato	Sugar beet	Potato	Winter wheat (Radish)
2012	Winter wheat (Italian ryegrass)	Winter wheat (Grass)	Winter wheat (Radish)	Potato

[1] Cover crops are indicated within parentheses.

3.2.4. Sampling and laboratory analyses

Earthworms were sampled following Van Vliet and De Goede (2006). Soil monoliths of 20 x 20 x 20 cm were dug out and handsorted for earthworms. To extract anecic earthworms 500 ml of 0.185% formaldehyde solution was applied to the bottom of the monolith pits. Earthworms were counted, weighed fresh, and species were identified using Sims and Gerard (1999) and Stöp-Bowitz (1969) for juveniles. Earthworm samplings were conducted during spring and autumn seasons when conditions are cool and moist and so favourable to earthworm activity.

Soil properties were measured to assess the influence of land management on soil and to then infer resultant impacts on earthworm species abundances using multivariate analysis. Composite soil samples were taken to 20 cm depth around each earthworm sampling location. Gravimetric soil moisture was measured at each sampling date by drying representative subsamples at 105°C for 24 hours. Soil moisture conditions were on average 220 $g\,kg^{-2}$. Additionally, soil samples pooled by distance from field margin strips, taken during the autumn 2010 earthworm sampling, were used to measure soil pH, texture (Kroetsch and Wang, 2008), total nitrogen (Novozamsky et al., 1984), and soil organic matter by loss-on-ignition (Normalisatie-Instituut, 1992).

3.2.5. STATISTICAL ANALYSES

Earthworm species abundance data, less abundant species in particular, did not meet the ANOVA normality assumption even after data transformation, therefore generalised linear models were used. Effects of distance (in the FM Experiment) and tillage (in the Tillage Experiment) on earthworm total abundance, biomass, species abundances, species richness, and adult/juvenile ratio were analysed using generalised linear mixed effects models (negative binomial error distribution) with repeated measures. Earthworm population structure can be used as an indication of disturbance or stress where stressed individuals fail to reach adulthood and reduce the adult/juvenile ratio (Klok and De Roos, 1996; Klok et al., 1997). Species richness was calculated on a per monolith basis. Farms were considered as replicates. Both farm and sampling date were considered random variables in the overall models whereas only farm was considered random in the models investigating effects per sampling date. A continuous first order autocorrelation was used for repeated measures. Standard diagnostic plots were used to check model assumptions. In the FM data analysis, lack of model convergence for *Allolobophora chlorotica* and *Aporrectodea limicola* for per sampling date models (farm and sampling date as fixed effects, Tables 3.3 and 3.5) necessitated a change in error distribution family to 'quasi', one of only two (Gaussian was the other) families that did not produce errors for both models.

Relations between management (i.e., field margin strips (FM), mouldboard ploughing (MP), and non-inversion tillage (NIT)) and soil properties, and between management and earthworm species abundances were explored using redundancy analysis (RDA). Data from the Tillage system and FM Experiments were combined in two separate redundancy analyses. The first RDA explored relations between management and soil properties measured during the autumn 2010 earthworm sampling (soil moisture, total soil nitrogen, soil organic matter, pH, and soil texture). Farm was included as a covariable. The second RDA explored relations between management and earthworm species abundances over all 4 sampling dates. Farm and sampling date were included as covariables. Only observations with no missing earthworm or soil property values could be included in RDA. Permutation tests were used to detect statistical significance of explanatory variables. All statistical computations were performed using 'MASS' (*glmmPQL*), 'lsmeans', and 'vegan' packages of R (Lenth, 2012; Oksanen et al., 2012; R Core Team, 2012; Venables and Ripley, 2002). The type I error rate (α) was set at ≤ 0.1 for all statistical tests.

3.3. RESULTS

3.3.1. DISTANCE FROM FIELD MARGIN STRIPS

In the Field Margin Strips (FM) Experiment a total of 11 earthworm species were found inside the FM, 12 species at 0.5 m, 9 at 30 m, and 9 at 60 m from field edges. Mean earthworm total abundance was 284 m^{-2} in field margin strips (FM), 154 m^{-2} at 0.5 m, 146 m^{-2} at 30 m, and 192 m^{-2} at 60 m (Tables 3.3 and 3.4). Mean earthworm total biomass was 84 $g\ m^{-2}$ in field margin strips (FM), 30 $g\ m^{-2}$ at 0.5 m, 28 $g\ m^{-2}$ at 30 m, and 34 $g\ m^{-2}$ at 60 m (Tables 3.3 and 3.4). When averaged over all samplings, *Aporrectodea rosea, Lumbricus rubellus, Lumbricus castaneus,* and *Lumbricus terrestris* abundances were significantly higher in FM than samples in MP fields (i.e., at least two of: 0.5 *m*, 30 *m*, or 60 *m* from field edges). *Aporrectodea caliginosa* was the dominant species in FM (54% of all individuals) and in arable fields (75-80% of all individuals) and their abundances did not vary significantly between FM and arable fields (30 *m*, or 60 *m* from field edges). *L. rubellus* abundance was lowest at 0.5 *m* from field edges over all samplings, significantly lower than in FM and 60 *m* from field edges. Mean species richness (calculated on a per monolith basis) overall samplings was 3.36 in FM, significantly higher than all other locations where species richness ranged between 1.70 and 1.86. Mean adult/juvenile ratio in field margin strips over all samplings was 0.96, however the value is skewed by the high ratio found in spring 2010. Median adult/juvenile ratio in field margin strips over all samplings was 0.41, and was significantly higher in FM than 30 *m* and/or 60 *m* from field edges at 3 of 4 samplings (Table 3.3).

3.3.2. Tillage comparison

In the Tillage Experiment a total of 9 earthworm species were found in non-inversion tillage (NIT) whereas 7 were found in mouldboard ploughing (MP). In NIT, mean earthworm total abundance was 275 m^{-2} and mean earthworm total biomass was 51 $g\,m^{-2}$ over all sampling dates and farms, significantly higher by 15% and 33% than MP plots respectively (Tables 3.5 and 3.6). NIT had significantly higher *L. rubellus* (165% higher) and *A. rosea* (79% higher) than MP overall. *L. terrestris* was also significantly higher in NIT (2.1 m^{-2}) than MP (0.2 m^{-2}), though numbers remained low throughout the study. *A. caliginosa* was the dominant species with 81% of all earthworms in MP and 71% in NIT. Mean species richness (calculated per monolith) overall samplings was 2.2 in NIT, significantly higher than 1.8 in MP. No difference in mean adult/juvenile ratio was found.

3.3.3. Soil properties and earthworms

Variation in soil properties used in redundancy analysis (RDA) of earthworm species abundances from FM and Tillage Experiments (combined data from Tables 3.3 and 3.5) are presented in Figure 3.2. Redundancy analysis of soil properties constrained by management (field margin strips (FM), mouldboard ploughing (MP), and non-inversion tillage (NIT)) are presented in Figure 3.3. Management explained 6% of total variance ($P < 0.01$, 100 permutations) in the partial RDA model with soil properties from autumn 2010. Farm (covariable) explained 59% of total variance. Figure 3.3 shows that FM contained higher soil organic matter (SOM) and total nitrogen (N_{tot}) but less clay than both MP and NIT. Soil moisture at the time of sampling was higher in FM and NIT than MP. Soil pH, N_{tot}, SOM, and moisture were negatively correlated with clay content.

A second RDA where earthworm species abundances from all sampling dates were constrained by management and distance from FM (in FM, 0.5 *m*, 30 *m*, and 60 *m*) is given in Figure 3.4. Soil moisture measured simultaneously with earthworm samplings did not explain a significant amount of variance in the RDA of earthworm species abundances and was therefore dropped from the model. Explanatory variables management and distance explained 7% of total variance (both $P < 0.01$, 100 permutations), and covariables farm and sampling date explained 5% of total variance. *Apporrectodea caliginosa* and *Lumbricus rubellus* were positively correlated, had higher abundance in NIT than FM and MP, and were negatively correlated with Distance-0.5 *m*. *A. caliginosa* was

Table 3.3: Earthworm abundances and biomass along transects from field margin strips.[1]

Sampling date	Distance	Total abundance (m^{-2})	Total biomass ($g\,m^{-2}$)	Adult/ juvenile ratio	*A. caliginosa* (m^{-2})	*A. rosea* (m^{-2})	*L. rubellus* (m^{-2})	*A. limicola* (m^{-2})	*L. terrestris* (m^{-2})	*L. castaneus* (m^{-2})	*A. chlorotica* (m^{-2})	Species richness
Spring 2010	FM	159(39)	49(14) a	1.48(0.28) a	72(27)	47(19)	9(5) ab	3(6)	3(4)	1(1)	2(3) b	2.65(0.34) a
	0.5 m	106(26)	28(8) ab	0.77(0.18) b	59(22)	17(7)	2(1) b	3(6)	1(1)	0(0)	12(3) a	2.00(0.27) ab
	30 m	116(29)	25(7) ab	0.46(0.13) b	71(26)	17(7)	12(6) a	0(6)	1(1)	0(0)	0(3) b	2.05(0.27) ab
	60 m	133(33)	24(7) b	0.43(0.12) b	79(29)	17(7)	19(9) a	1(6)	0(0)	0(0)	0(3) b	1.74(0.24) b
Autumn 2010	FM	287(71) a	107(30) a	0.87(0.21) a	144(55)	58(23) a	23(11) a	7(6)	9(1) a	10(13) a	1(3)	3.62(0.44) a
	0.5 m	250(26) ab	47(13) b	0.74(0.18) a	151(56)	41(17) ab	2(1) c	5(6)	3(3) ab	2(2) b	8(3)	2.25(0.30) b
	30 m	155(38) b	34(10) b	0.36(0.11) b	119(44)	12(5) b	5(2) ac	11(6)	1(1) b	0(0) ab	0(3)	1.51(0.22) c
	60 m	243(60) ab	47(13) b	0.46(0.13) ab	171(63)	17(7) ab	13(6) ab	7(6)	0(0) ab	0(0) ab	0(3)	1.88(0.26) bc
Autumn 2011	FM	405(100) a	101(28) a	0.90(0.20) a	196(73) a	54(22) a	33(15) a	53(6) a	12(15) a	3(4) a	11(3) a	3.77(0.46) a
	0.5 m	96(24) b	21(6) b	0.56(0.15) ab	66(25) bc	5(2) b	0(0) ab	14(6) b	0(1) b	1(1) b	5(3) ab	1.40(0.21) b
	30 m	139(35) b	33(10) b	0.44(0.13) b	105(39) ab	11(5) b	5(3) b	3(6) b	1(1) b	1(1) b	0(3) b	1.60(0.23) b
	60 m	154(38) b	33(9) b	0.73(0.17) ab	94(35) bc	6(3) b	11(5) ab	15(6) ab	1(1) b	0(0) ab	4(3) ab	1.68(0.23) b
Spring 2012	FM	231(57) a	52(14) a	0.36(0.12) b	104(39) ab	43(17)	22(10) a	11(6)	8(10)	4(5) a	2(3)	3.20(0.40) a
	0.5 m	122(30) b	18(5) b	0.70(0.19) a	76(28) b	18(8)	3(2) b	12(6)	0(1)	0(1) b	0(3)	1.69(0.24) b
	30 m	136(34) ab	14(4) b	0.26(0.11) b	112(41) ab	21(9)	5(3) ab	3(6)	0(0)	0(0) ab	0(3)	1.62(0.23) b
	60 m	214(53) a	24(7) b	0.14(0.08) b	177(66) a	14(6)	9(5) ab	0(6)	0(1)	0(0) ab	0(3)	1.67(0.23) b
Overall means	FM	268(51) a	73(15) a	0.91(0.16) a	127(40) a	50(13) a	22(6) a	7(5) a	10(10) a	4(4) a	1(1) ab	3.29(0.27) a
	0.5 m	137(26) c	27(6) b	0.69(0.13) b	84(27) b	18(5) b	2(1) c	4(3) ab	1(1) b	0(1) b	1(1) a	1.84(0.16) b
	30 m	133(25) c	24(5) b	0.38(0.09) c	96(31) ab	14(4) b	7(2) b	1(1) c	1(1) b	0(0) b	0(0) b	1.70(0.15) b
	60 m	182(35) b	31(6) b	0.44(0.09) c	125(40) a	12(3) b	13(3) ab	2(2) b	1(1) b	0(0) b	0(0) ab	1.75(0.15) b

[1] Mean total abundance, total biomass, and species abundances are given with standard errors in parentheses. Sampling locations were in the grassy field margin strips (FM) and 0.5 m, 30 m, and 60 m from field edge. Most abundant species present were *Aporrectodea caliginosa*, *Aporrectodea rosea*, *Lumbricus rubellus*, *Aporrectodea limicola*, *Lumbricus terrestris*, *Lumbricus castaneus*, and *Allolobophora chlorotica*. Species with > 1% of overall abundance are included, other species present were *Satchellius mamalis*, *Aporrectodea longa*, *Murchieona minuscula*, *Eiseniella tetraedra*, and *Dendrodrilus rubidus*. Species abundance columns are ordered from left to right by decreasing overall abundance. Letters indicate significant treatment differences at $P \leq 0.1$ between sampling locations within each sampling date. Adults and juveniles are combined, except for adult/juvenile ratio.

Table 3.4: Summary of GLMM output for Field Margin Strips Experiment.

	Total abundance	Total biomass	A/J ratio[1]	*Aporrectodea caliginosa*	*Aporrectodea rosea*	*Lumbricus rubellus*	*Aporrectodea limicola*	*Lumbricus terrestris*	*Lumbricus castaneus*	*Allolobophora chlorotica*	Species richness
Fixed effects (p-values)											
(Intercept)	0.00	0.00	0.57	0.00	0.00	0.00	0.01	0.03	0.23	0.89	0.00
Distance 0.5 *m*	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.46	0.00
Distance 30 *m*	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.99	0.00
Distance 60 *m*	0.00	0.00	0.00	0.91	0.00	0.15	0.01	0.00	1.00	0.03	0.00

[1] Adult/juvenile ratio

3

Table 3.5: Earthworm abundances and biomass in non-inversion tillage and mouldboard ploughing plots.[1]

Sampling date	Tillage system	Total abundance (m^{-2})	Total biomass ($g\,m^{-2}$)	Adult/ juvenile ratio	*Aporrectodea caliginosa* (m^{-2})	*Lumbricus rubellus* (m^{-2})	*Aporrectodea rosea* (m^{-2})	*Aporrectodea limicola* (m^{-2})	Species richness
Spring 2010	MP	139(24)	33(6)	0.21(0.14)	111(19)	15(7)	14(4)	1(1)	1.79(0.20)
	NIT	158(27)	40(7)	0.30(0.19)	121(21)	12(5)	14(4)	0(0)	1.72(0.20)
Autumn 2010	MP	280(47)	69(12)	0.48(0.27)	221(38)	22(9)	16(5)	2(1)	1.97(0.22)
	NIT	310(53)	68(12)	0.88(0.46)*	220(37)	37(15)	27(7)	3(3)	2.18(0.24)
Autumn 2011	MP	222(40)	30(6)	0.33(0.20)*	183(33)	14(6)	11(3)	0(0)	1.71(0.22)
	NIT	312(62)	46(10)	0.06(0.06)	253(50)	39(18)*	28(8)*	3(3)	2.31(0.28)*
Spring 2012	MP	175(42)	33(8)	0.09(0.08)	144(35)	16(9)	14(6)	0(0)	1.87(0.28)
	NIT	275(48)	42(8)	0.18(0.13)	168(28)	36(15)	36(10)*	1(1)	2.82(0.33)*
Overall average	MP	185(28)	36(5)	0.42(0.09)	144(21)	13(5)	14(2)	2(1)	1.85(0.15)
	NIT	225(33)*	44(6)°	0.43(0.09)	165(24)	22(8)*	25(4)*	2(1)	2.16(0.16)*

[1] Mean total abundance, total biomass, and species abundances are given with standard errors in parentheses. Tillage systems are non-inversion tillage (NIT) and mouldboard ploughing (MP). Species with > 1% of overall abundance are included, other species present were *Lumbricus terrestris*, *Lumbricus castaneus*, *Allolobophora chlorotica*, *Murchieona minuscula*, *Aporrectodea longa*, and *Satchellius mamalis*. Species abundance columns are ordered from left to right by decreasing overall abundance. Significant differences between tillage systems within sampling dates are indicated by ° $P \leq 0.1$, *$P \leq 0.05$. Adults and juveniles are combined, except for adult/juvenile ratio.

3

Table 3.6: Summary of GLMM output for Tillage Experiment.

	Total abundance	Total biomass	Adult/ juvenile ratio	*Aporrectodea caliginosa*	*Lumbricus rubellus*	*Aporrectodea rosea*	*Aporrectodea limicola*	Species richness
Fixed effects (p-values)								
(Intercept)	0.00	0.00	0.00	0.00	0.00	0.00	0.51	0.00
Tillage (NIT)	0.05	0.07	0.90	0.19	0.01	0.02	0.88	0.04

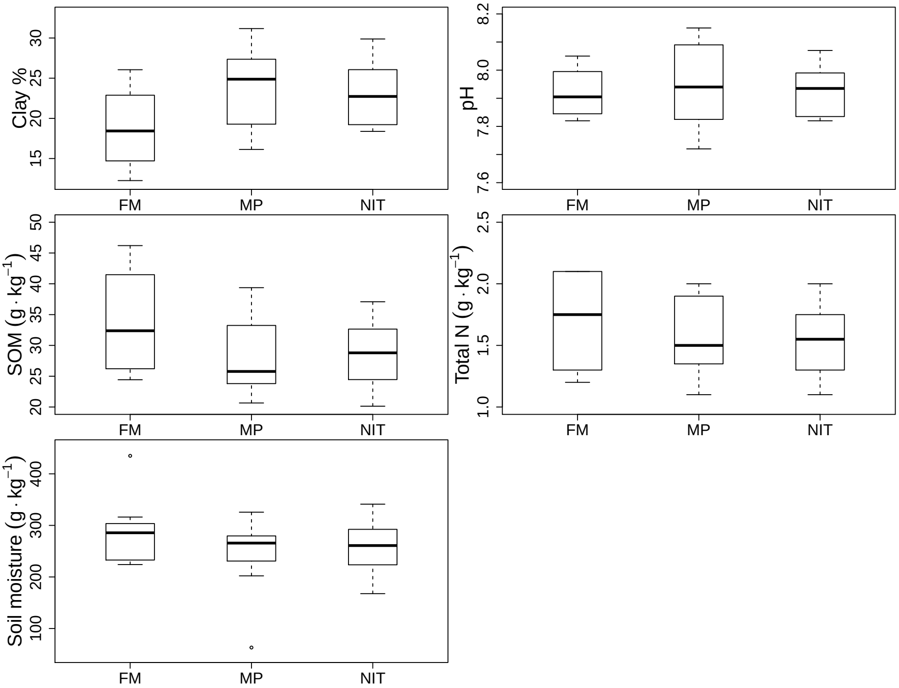

Figure 3.2: Soil properties from autumn 2010 used in redundancy analysis. Data from the tillage comparison and field margin transects were combined. Non-inversion tillage (NIT, n=8; n=30 for soil moisture), mouldboard ploughing (MP, n=15)(n=63 for soil moisture), and field margin strips (FM, n=4; n=16 for soil moisture) are displayed.

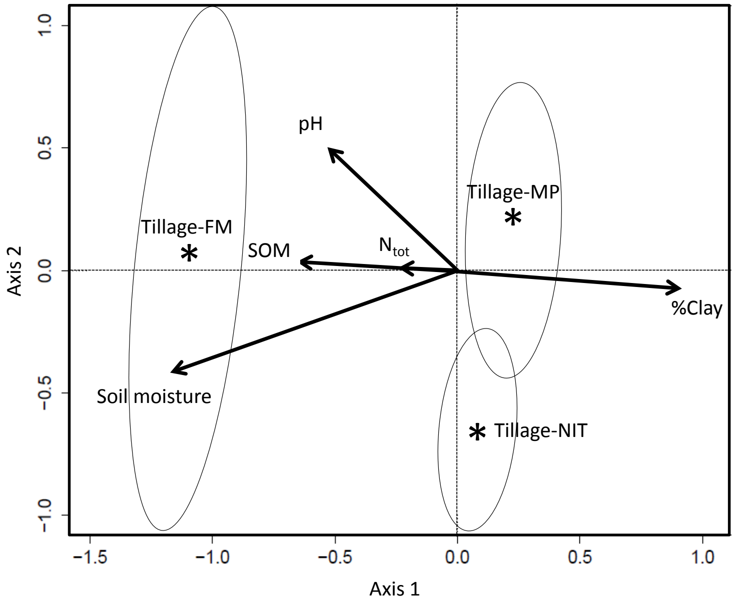

Figure 3.3: Redundancy analysis biplot of soil properties from autumn 2010 ($P < 0.01$) constrained by management (field margin (TillageFM), mouldboard ploughing (TillageMP), and non-inversion tillage (TillageNIT)($P = 0.01$)) with farm as covariable. The first RDA axis explains 14% of variance, the second RDA axis 0.4%, the first PCA axis 33%, and the second PCA axis 27% after variance due to farm was removed (59% of total variance). Confidence intervals (95%) are indicated by ellipses around class centroids.

not correlated, and *Eiseniella tetraedra* was negatively correlated with FM whereas all other earthworm species abundances were positively correlated and higher in FM.

3.4. DISCUSSION

3.4.1. EARTHWORMS IN FIELD MARGIN STRIPS

In general, field margin strips (FM) had higher total earthworm abundance and biomass, as well as individual species abundances, than adjacent arable fields. However this did not result in a gradient of earthworm abundance into adjacent arable fields. *L. terrestris*, a species considered important for soil water infiltration (Shipitalo and Le Bayon, 2004) and crop residue incorporation (Curry and Bolger, 1984), remained at negligible levels in arable fields even though abundances were significantly higher in adjacent FM. Little is known about the distribution of *L. terrestris* in The Netherlands. In a survey of 42 grassland and horticultural sites across The Netherlands Didden (2001) only found *L. terrestris* on 2.4% of sites. The epigeic species *L. rubellus* and *L. castaneus* were most abundant in FM relative to NIT and MP. In a study conducted in England, fields with grassy field margin strips contained higher earthworm species abundances than fields without strips, however abundances in adjacent arable fields were not affected by presences of

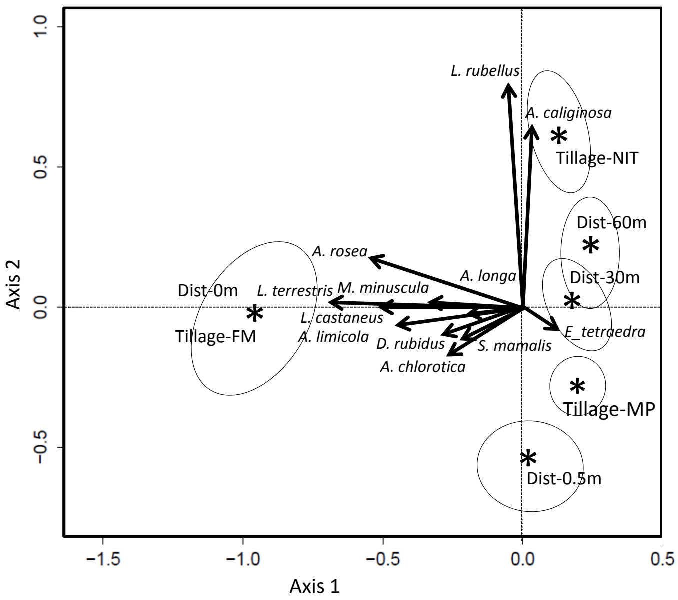

Figure 3.4: Redundancy analysis (RDA) biplot of earthworm species abundances from all samplings ($P < 0.01$) in Field Margin Strips and Tillage system Experiments. RDA constraints were management (field margin strips (TillageFM), mouldboard ploughing (TillageMP), non-inversion tillage (TillageNIT)($P = 0.01$)) and distance from field edge (Dist0 (TillageFM), Dist0.5 m, Dist30 m, or Dist60 m ($P = 0.01$)), farm and sampling date as covariables. Partitioning of correlation: 5.3% covariables, 6.7% constraints. The first RDA axis explains 4.6% of variance, the second RDA axis 2.0%, the first PCA axis 12%, and the second PCA axis 10% after variance due to farm and sampling date were removed. Species displayed are: *Aporrectodea caliginosa*, *Aporrectodea rosea*, *Lumbricus rubellus*, *Aporrectodea limicola*, *Lumbricus castaneus*, *Lumbricus terrestris*, *Allolobophora chlorotica*, *Satchellius mamalis*, *Aporrectodea longa*, *Murchieona minuscula*, *Eiseniella tetraedra*, and *Dendrodrilus rubidus*. Confidence intervals (95%) are indicated by ellipses around class centroids.

strips (Smith et al., 2008), in accordance with the current study. In a recent study, Roarty and Schmidt (2013) studied earthworms in permanent and new field margin strips, and in adjacent arable fields over a 3 year period. Earthworm abundance and biomass was 3-fold higher in field margin strips than adjacent conventionally ploughed fields on average (Roarty and Schmidt, 2013). However, as in the current study, these margins did not enhance earthworm populations in near-by arable fields.

Anecic species were almost non-existent outside of field margin strips. Burrow destruction by tillage operations, use of heavy machinery at harvest, insufficient food quantity or inaccessible food may account for low anecic abundances (Chan, 2001; van Capelle et al., 2012). Arable fields under reduced tillage in combination with adjacent field margin strips may provide greater opportunity for earthworm species that require less disturbed soil and greater food availability at the soil surface to migrate (e.g., *L. terrestris*). However, this is not supported by Roarty and Schmidt (2013), who conclude that field margin strips support *L. terrestris*, but that reduced tillage does not benefit earthworm dispersal from field margins strips relative to ploughing. It may be that more time is needed for *L. terrestris* to establish in arable fields under reduced tillage. Nuutinen et al. (2011) reported that inoculated *L. terrestris* did not spread from field margins and inoculation points in significant numbers after 5 years, however after 13 years a clear gradient with distance from field margin strips and inoculation points had established into arable fields under no-tillage. *L. castaneus*, was found to be more abundant in field margin strips than in adjacent arable fields in the current study, which is corroborated by Nieminen et al. (2011). *L. rubellus*, also epigeic, was similarly more abundant in FM than in arable fields at all distances from field edge. Furthermore, *L. rubellus* abundances were lowest at 0.5 m from field edge compared to other distances along transects in the current study. *L. rubellus* may have preferred FM over 0.5 m from field edge because FM contains more food resources. As an epigeic species *L. rubellus* spends more time at or near the soil surface relative to other species and thus has greater opportunity for mobility. *L. rubellus* dispersal rates in Dutch polders have been estimated at 11 $m\,y^{-1}$ and experimentally found to be 5 $m\,y^{-1}$ (Marinissen, 1991; Marinissen and Van den Bosch, 1992). Also, since the field edge is the headland in some cases it may receive a greater number of tractor passes and have higher soil compaction which can limit *L. rubellus*.

3.4.2. Earthworms as affected by tillage systems

Non-inversion tillage (NIT) significantly increased earthworm total abundance, total biomass, and species abundances relative to mouldboard ploughing (MP) over all samplings in the Tillage Experiment. This confirms the hypothesis that NIT increases earthworm numbers relative to MP. An increase in species abundances with time cannot conclusively be attributed to a cumulative tillage system effect since it could not be disentangled from the influence of crop and climatic conditions. NIT consists of a less intensive soil manipulation than MP, though it is still more disruptive than strict no-till systems (Morris et al., 2010; Tebrügge and Düring, 1999). In NIT crop residues are left at the soil surface and more opportunity for cover crops exist in autumn, both of which may contribute to higher earthworm numbers relative to MP systems (Holland, 2004; Morris et al., 2010; Peigné et al., 2007). Even though individual earthworm species abundances were higher in NIT than MP, the anecic species abundances (*Lumbricus terrestris* and

Aporrectodea longa) remained very low in arable fields. Anecic species may not benefit from NIT systems because tillage operations (e.g., seed bed preparation, weed control) in NIT may still be too disruptive to burrows, insufficient organic matter may be retained, crop rotations that include tuber crops (e.g., potato, sugar beet) that require intensive ridge building operations and heavy machinery for harvest are too damaging, or insufficient time has passed for population increase to have occurred (Curry, 2004; Curry et al., 2002; Marinissen, 1992; Nuutinen et al., 2011).

Reduced tillage in the current study had a positive effect on *Lumbricus rubellus*, likely due to retention of crop residues at the soil surface. On the other hand, Ernst and Emmerling (2009) found no significant tillage effect on epigeic earthworms. The endogeic species *Aporrectodea caliginosa* made up 70% of all earthworms in the current study and was more dominant in MP (75-81%) than NIT (71%) and FM (54%). This dominance by endogeic species, *A. caliginosa* in particular, in arable systems is congruent with previous findings (De Oliveira et al., 2012; Marinissen, 1992; Nieminen et al., 2011).

3.4.3. EARTHWORM, SOIL PROPERTY, AND MANAGEMENT RELATIONS

Earthworm species assemblages were similar to those of other studies conducted in Dutch polder soils (Faber and Hout (2009); Van der Werff et al. (1998) and Chapter 2 of this thesis). Studies conducted in arable and grassland sites in north-western Europe also had similar earthworm assemblages to the current study (De Oliveira et al., 2012; Ernst et al., 2009; Nieminen et al., 2011; Valckx et al., 2009).

Integration of earthworm species abundance data from the FM and Tillage Experiments by multivariate analysis (Fig. 3.4) confirmed relations revealed by generalised linear models (Tables 3.3 and 3.5). Fig. 3.4 confirms that *L. rubellus* and *A. caliginosa* were more abundant in NIT than MP, and that many of the less common earthworm species (i.e., *L. terrestris, L. castaneus*) were more abundant in FM than adjacent arable soil. Redundancy analysis, in addition, showed that FM contained higher earthworm species abundances than MP or NIT for most species, indicating that FM can support more diverse earthworm communities than adjacent arable soil (Nieminen et al., 2011; Smith et al., 2008). Earthworms in FM likely benefited from higher SOM and soil moisture relative to adjacent arable soil (Fig. 3.3) and from reduced soil disturbance and a permanent food source (Roarty and Schmidt, 2013; Smith et al., 2008). FM also contained less clay than the arable soils (NIT, MP; see Figure 3.2) probably as a result of deposition of ditch dredging material (Strien et al., 1989)

Soil properties measured in the current study are known to affect earthworm species abundances (Curry, 2004), however soil properties varied relatively little across farms located within the same landscape (Fig. 3.2), and therefore likely had small influence on variation in earthworm species abundances. Additional soil properties (e.g., bulk density) could help explain variation in earthworm species abundances. Even though farm accounted for a large part of the variance in soil property data (59%, Fig. 3.3) it contributed, together with sampling date, only 5% of variance in earthworm species abundances (Fig. 3.4). Management (MP, NIT, FM) and differences in environmental conditions between sampling dates likely had a greater influence than farm due to the small variation in soil properties between farms. Significant management effects on earthworm species abundances across farms were detected despite large temporal variation (see Tables 3.3 and 3.5).

3.5. Conclusions

Field margin strips and non-inversion tilled soil harboured higher earthworm numbers and more species than adjacent arable fields under mouldboard ploughing. However, anecic earthworm species (i.e., *Lumbricus terrestris*), considered important contributors to soil functioning, were virtually absent in mouldboard ploughed soil regardless of their presence in nearby field margin strips or in soil under non-inversion tillage. Soil disturbance and compaction resulting from crop rotations including sugar beets and potatoes and lack of crop residues (food for earthworms) left at the soil surface likely played a role. Field margin strips and tillage system effects on earthworm numbers were apparent in this on-farm study, conducted at multiple locations, even with variation due to changes in climatic conditions between samplings and heterogeneity between farms. The combination of decreased soil disturbance associated with tuber crops and increased duration of reduced tillage and non-crop areas may entice anecic species from adjacent non-crop areas, but further (longer term) studies are needed to confirm this. Functional agrobiodiversity programs that promote non-crop areas and reduced tillage can benefit earthworm abundance and diversity.

4

SOIL PHYSICAL QUALITY IN CONTRASTING TILLAGE SYSTEMS IN ORGANIC AND CONVENTIONAL FARMING

This chapter has been published in Crittenden et al. (2015b).


soil
tillage
org
organic
cm
water
MP
NIT
conv
systems
conventional
farming
ploughing
depth
spring
reduced
Soil
content
autumn
mouldboard
crop
density
non-inversion
higher
carbon
yield
retention
aggregate
matter
hydraulic
resistance
stability
physical
conductivity
field-saturated
bulk
effects
structure
differences
stocks
measured
increased
may
significantly
Significant
Penetration
wheat
beet
increase
fields
system
treatment
penetration
measurements
taken
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used
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study
SOM
SOC
infiltration
quality
plot
structural
Table
Organic
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Hp
sampling
operations
i.e
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dry
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sugar
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Reduced tillage can improve soil physical quality relative to mouldboard ploughing by lessening soil disturbance, leaving organic matter at the soil surface, and stimulating soil biological activity. In organic farming, continuous ploughing may negate benefits to soil structure and function from increased use of manures and more diverse crop rotations, which are particularly important components of organic farming. The current study examined soil physical quality (i.e., properties and functioning) of a 4-year old reduced tillage system under organic and conventional farming with crop rotations that included root crops. Reduced tillage was compared to conventional mouldboard ploughing (MP) in 2 organic fields at different points of the same crop rotation (Org A and Org B) and 1 conventional field (Conv A). Reduced tillage consisted of non-inversion tillage (NIT) to 18-23 cm depth whereas MP was characterised by annual mouldboard ploughing to 23-25 cm depth. NIT improved soil water retention in Org B but had no effect in Org A. NIT increased soil aggregate stability at 10–20 cm depth compared to MP in all fields, and additionally at 0–10 cm in Conv A. Penetration resistance was higher in NIT in all fields. Furthermore, soil organic matter content was higher in NIT than MP at 0–10 cm depth in all fields and at 10–20 cm in Org B and Conv A. NIT increased carbon stocks in Org B but not in Org A. NIT statistically increased crop yields in spring wheat/faba bean mixture in Org A, and there was no yield penalty from NIT in Org B spring wheat nor Conv A sugar beet. In contrast, field-saturated hydraulic conductivity in all fields in autumn was lower in NIT. Differences in crop (i.e., phase of rotation) and associated organic inputs between Org A and B likely accounted for the differences in effects of tillage system. Overall, the NIT system improved or imposed no penalty on soil physical quality (except field-saturated hydraulic conductivity) and improved or imposed no penalty on crop yields and could therefore be considered as a viable alternative for farmers.

4

4.1. INTRODUCTION

Reduced soil tillage systems aim at improving soil physical quality and at decreasing risk of drought and water logging. Reduced tillage systems also known to increase soil organic matter, improve soil biodiversity, and reduce production costs (El Titi, 2003; Morris et al., 2010; Soane et al., 2012). Conventional mouldboard ploughing systems invert soil during primary tillage operations to control weeds, incorporate organic material (i.e., crop residues and manures), and loosen top soil. Mouldboard ploughing (MP), and tillage in general, increase porosity on the short term but decrease stable soil aggregation over the long term (Bronick and Lal, 2005), and can reduce soil organic matter content, deteriorate soil structure, lower water-holding capacity, and compact subsoil (Lal et al., 2007; Munkholm et al., 2008).

Reduced tillage increases soil stability due to less physical disruption of aggregates (D'Haene et al., 2008), soil carbon may increase from greater protection inside aggregates and less exposure to oxygen (Kay and Vandenbygaart, 2002), and subsoil compaction may be decreased if machinery only drives on the soil surface and not the subsoil as is often done in MP (Chamen et al., 2003). Reduced soil disturbance that promotes soil life may increase soil organic matter content and improve macroporosity and thereby infiltration rates (Martens and Frankenberger, 1992). However, reduced tillage systems have also been shown to increase medium sized water holding pore volumes while decreasing large water conducting pores (Rasmussen, 1999). Soils under reduced tillage systems in northern Europe tend to warm slowly in spring because of high water contents that reduce trafficability, seedling emergence, and crop yield (Rasmussen, 1999; Soane et al., 2012).

Non-inversion tillage, and reduced tillage more broadly, tend to cause increases in bulk density due to natural reconsolidation (Ahuja et al., 1998) and are therefore at risk of lowering yield (Arvidsson et al., 2014). In a meta-analysis of European studies that investigated the effects of tillage systems (conventional, reduced, and no-tillage) deep reduced tillage (>0.15 m depth) only decreased yields for maize and not for root crops, and in many cases yield losses were compensated by lower production costs (Van den Putte et al., 2010).

Reduced tillage systems such as non-inversion tillage (NIT) are implemented as an alternative to systems with MP as primary tillage in temperate north-western European conditions. NIT may consist of sub-soiling or chiseling at shallower depth and can be used in crop rotations that include root and tuber crops that require intensive soil disturbance during ridge building and are subjected to compaction from heavy harvesting machinery (D'Haene et al., 2008). In addition to tillage system and main crop, the soil physical environment is also affected by farming system, cover crop, and trafficking. Organic and conventional farming systems have been compared in The Netherlands. Organic farming may have higher soil water supply capacity and thus higher potential water-limited crop yields relative to conventional farming (Droogers et al., 1996). Organic farming may also yield higher soil organic matter content and stable aggregation than conventional farming but may cause higher risk of soil compaction (Droogers et al., 1996; Pulleman et al., 2003). There is a particular lack of studies focusing on reduced tillage in organic farming (Gadermaier et al., 2012). Confirmation, therefore, is needed on the effects of NIT on soil physical quality in organic and conventional farming under Dutch soils and crops.

NIT affords an increased window of opportunity for cover crops where ploughing would normally occur in autumn which may bring additional effects to soil physical quality. Cover crops are acknowledged to promote soil and ecosystem functions, in particular cover crops benefit soil carbon and nitrogen, weed suppression, and erosion control (Schipanski et al., 2014). Crops with deep tap roots, radish for example, have been reported to decrease soil compaction since they are able to penetrate and loosen compacted soils (Hamza and Anderson, 2005).

The objective of this study was to compare NIT to the standard MP practice in terms of soil physical functions (i.e., soil water retention and field-saturated hydraulic conductivity), soil structural parameters (i.e., aggregate stability, penetration resistance, and bulk density), soil organic matter, and crop yield. In addition, we aimed to assess the effect of non-inversion tillage on soil organic carbon stocks and depth distribution along the soil profile.

4.2. MATERIALS AND METHODS

4.2.1. SITE DESCRIPTION

The study was carried out at the PPO Lelystad experimental farm ($52°32'N, 5°34'E$) of Applied Plant Research Wageningen UR, The Netherlands. The soil is a calcareous marine clay loam (22% clay, 10% silt, 68% sand), with a pH of 7.9. Average annual temperature is 9.7° C and average annual precipitation is 825 mm (Royal Netherlands Meteorological Institute, 2013).

4.2.2. EXPERIMENTAL DESIGN

The research farm maintains a set of fields under conventional farming and organic farming that contain the tillage experiments (Fig. 4.1). Two fields under organic farming and one field under conventional farming were used in this study. All fields contained the same tillage systems arranged in randomised complete block designs with 4 blocks. Tillage systems were mouldboard ploughing (MP) and non-inversion tillage (NIT). Organic field A (Org A) and Organic field B (Org B) are separated by approximately 200 m (Fig. 4.1). Fields became certified organic in 2004 (certification number: 006211). Org A, Org B, and Conventional field A (Conv A) from Chapter 2 of this thesis are used here.

After the last ploughing of all plots in autumn 2007 the experimental tillage systems were established in autumn 2008 in both conventional and organic fields. Soil was subsoiled to 30 cm depth to break up the existing plough pan at the start of the experiment. All farm operations, except harvest and ploughing, are performed using controlled-traffic farming permanent tracks spaced at 3.15 m apart. In conventional MP soil is mouldboard ploughed in autumn to a depth of 23-25 cm and in NIT soil is subsoiled annually in autumn after harvest using a Kongskilde Paragrubber up to a depth of 18-23 cm. A shallow cultivation till 8 cm depth was performed for seedbed preparation of main and cover crops.

A six-year crop rotation of potatoes, grass clover, cabbage, spring wheat, carrots and faba bean/spring wheat mixture was used in Org A and B (Table 4.1). Conv A had a 4-year crop rotation of wheat or barley, onion, potato, and sugar beet. Regular weeding operations were done by mechanical and manual hoeing (organic fields) and a weeding harrow. Organic fields A and B receive $20-40\,\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ (fresh weight) slurry and/or solid cow manure, whereas leguminous crops and carrots receive no manure in general. Conv A received inorganic fertilisers, no animal manures, and yearly pesticide applications adherent to local convention.

Org A was sampled in autumn 2011 and Org B and Conv A were sampled in spring 2012. During sampling in autumn 2011 (September/October) Org A had faba bean/spring wheat mixture, and in spring 2012 (May) Org B had spring wheat and Conv A had sugar beet. Different organic fields were used because Org A had potatoes in spring 2012 and sampling of soil physical properties is problematic in potato ridges.

Table 4.1: Crop rotation per field (cover crop/green manure)

Year\Field	Org A	Org B	Conv A
2009	Spring wheat (white clover)	Potato (grass clover)	Spring barley (Italian rye grass)
2010	Carrot	Grass clover (grass clover)	Onion
2011	Spring wheat/faba bean mixture (yellow mustard)	White cabbage	Potato (rye grass)
2012	Potato (grass clover)	Spring wheat (winter fetch)	Sugar beet
2013	Grass clover (Grass clover)	Carrot	Spring barley (yellow mustard/fetch/facelia)
2014	White cabbage	Spring wheat/faba bean intercrop (yellow mustard)	Onion (yellow mustard)

4.2.3. Soil water retention

Undisturbed 100 cm^3 soil cores were collected at 0–5 cm and 10–15 cm depths in autumn 2011 and spring 2012 from three evenly spaced locations in each plot. Soil water retention was measured using a combination of the sand box and suction plate methods (Normalisatie-instituut, 1994a) at pressure heads h = 0, 10, 20, 100, 155, 310 and 619 cm, additionally 50 cm in spring 2012, plus 1580 and 15500 cm using the pressure plate (Normalisatie-instituut, 1994b). Soil water retention was not measured in Conv A.

4.2.4. Field-saturated hydraulic conductivity

Water infiltration rate was measured using a falling head double-ring infiltrometer method (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) to approximate field-saturated hydraulic conductivity (K_{fs}). Plant residue material that could impede ring insertion was removed beforehand. Metal rings of 30 cm and 50 cm diameter were driven 5 cm into the soil surface. Inner and outer rings were then filled with water. Water was poured onto sponges placed inside the rings to reduce slaking the soil surface. Water heights were recorded in the inner ring every minute until three consecutive water infiltration rate readings were within 10% of each other. This value was considered as the field-saturated hydraulic conductivity. High spatial and temporal variability in field-saturated water flow parameters requires extensive measurement repetition (Reynolds et al., 2002). Therefore, multiple measurement sets (i.e., filling the rings with water) were performed at each measurement location and three sets of measurements were performed per plot per sampling date. The last of each set of measurements per location was used to estimate the field-saturated hydraulic conductivity. Water infiltration measurements were taken in Org A during May 2011 to represent early crop growth, and in September and October 2011 (i.e., before and after crop harvest and before mouldboard ploughing and non-inversion tillage operations). Water infiltration measurements in Org B and in Conv A were taken in May 2012 after sowing and in November 2012 after

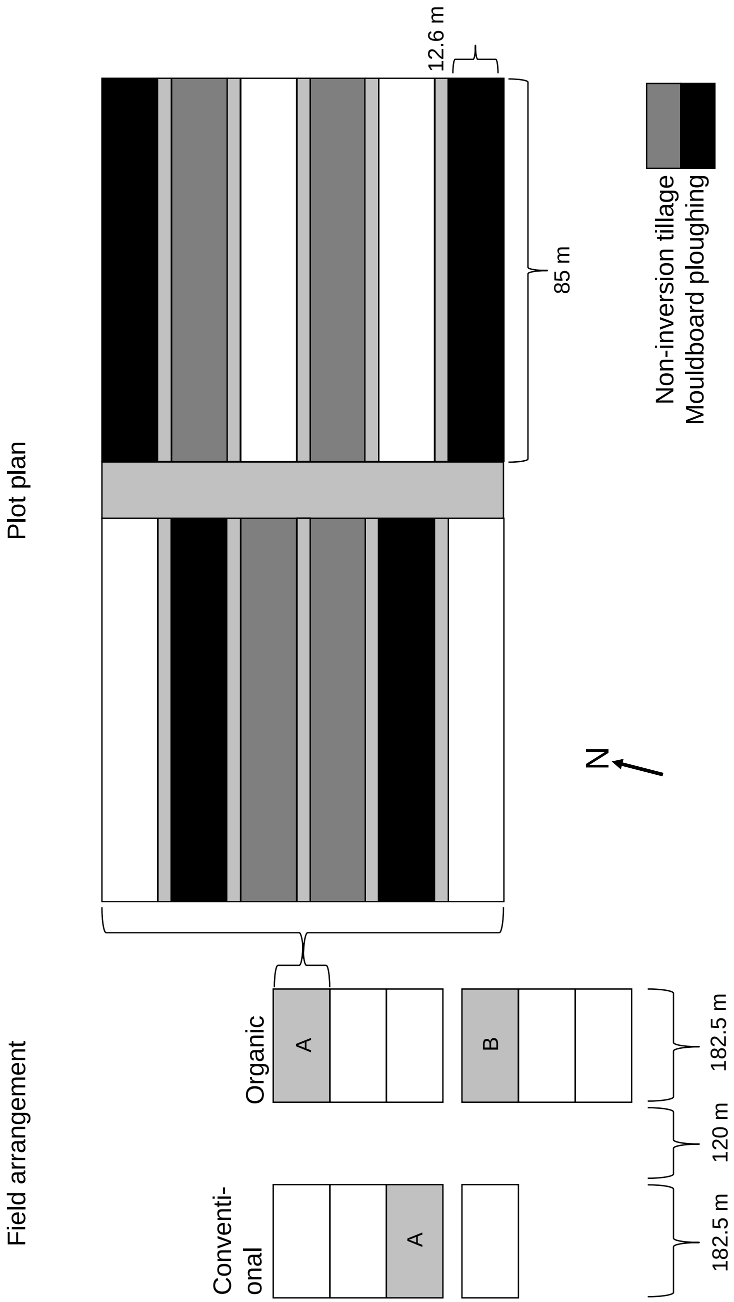

Figure 4.1: Arrangement of experimental fields and plots

sugar beet harvest and before mouldboard ploughing/non-inversion tillage.

4.2.5. Soil water content

Soil water content was determined gravimetrically to 20 cm depth (n=3 per plot) in autumn 2011 and spring 2012 at the time of sampling other soil physical parameters. Soil was oven dried at 105°C for 24 hours (autumn 2011 samples) and at 40°C for 48 hours (spring 2012) and re-weighed.

4.2.6. Aggregate stability

Soil aggregate stability was determined in Org A, Org B, and Conv A by wet sieving according to Elliott (1986). Three undisturbed soil samples (10 x 10 x 10 cm) were taken per plot at both 0–10 and 10–20 cm depths. The samples were gently broken up along natural planes of weakness, passed through a 10 mm sieve and dried at room temperature. A representative sub-sample was weighed and spread out evenly on a 2 mm sieve placed in distilled water. After submersion in water for five minutes samples were oscillated 50 times in two minutes. Water and soil that passed through the 2 mm sieve was transferred to a basin with a 250 μm sieve and after repeating the oscillations, to a 53 μm sieve. The remaining soil on each sieve, and material having passed through the 53 μm sieve, was dried at 80°C and left for at least 16 hours. After oven drying, weights of aggregate size classes were used to calculate mean weight diameter (Van Bavel, 1950).

4.2.7. Dry bulk density

Bulk density was determined using soil cores taken for water retention curves (Section 4.2.3) in Org A in autumn 2011 and Org B in spring 2012 (0–5 cm and 10–15 cm). These soil samples of known volumes, as described in Section 4.2.3, were weighed, oven dried at 105 °C for 24 hours and weighed again to calculate dry bulk density (g cm^{-3}).

4.2.8. Penetration resistance

Penetration resistance (PR), an indication of ease of root penetration (Bengough and Mullins, 1991), was measured with a penetrologger (Eijkelkamp Agrisearch 2011, 1 cm^2 cone diameter 60°) in autumn 2011 in Org A and in spring 2012 in Org B, and spring 2013 in Conv A. Penetrologger data from spring 2012 in Conv A are not available, though measurements were repeated in spring 2013. In each plot 14 profiles were taken in autumn 2011 and 10 profiles per plot in spring 2012 and spring 2013, all to 80 cm depth with a 1 cm depth resolution. Penetration resistance data are limited to 50 cm depth as this is just below the maximum depth of tillage and measurement error below this depth increased greatly making meaningful inference difficult.

4.2.9. Soil organic matter content and carbon stocks

Soil cores used to measure soil organic matter content (SOM) were taken in autumn 2011 using a hydraulic soil sampler (Nietfeld Bodenprobetechnik NH 90, 2.55 cm^2) at 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–50 cm depths. This sampling method was chosen to minimise soil disturbance. Based on the known volume of the hydraulic soil sampler the dry bulk density could be calculated after drying the soil samples for the indicated depth intervals. Bulk densities were calculated in Org A in autumn 2011. However, soil in the top 20 cm did not properly fill the borer used to collect soil for SOM content measures and therefore bulk densities were calculated using soil water retention curve samples instead (Sections 4.2.3 and 4.2.7). In spring 2012 in Org B and Conv A SOM was measured on samples taken for aggregate stability (Section 4.2.6).

SOM content was measured by weight change after loss-on-ignition (Normalisatie-Instituut, 1992). Soil samples were first dried at 105 °C for 24 hours. SOM was then calculated by weight loss after heating to 550 °C and subtracting 7% of the weight of the clay fraction (representing water in the clay structure) (Normalisatie-Instituut, 1992). To compare carbon stocks in tillage systems SOM was corrected for dry bulk density to obtain SOM content on an equivalent soil mass basis for Org A and Org B (Ellert and Bettany, 1995). A SOM to SOC conversion factor of 0.41 was determined (Poot, 2012) using half of the samples from autumn 2011 (20 out of 40) using the Kurmies method (Medius, 1960).

4.2.10. CROP YIELD

Spring wheat/faba bean mixture in Org A in 2011 and spring wheat in Org B in 2012 were harvested on standard tracks with a combine. Fresh marketable crop yield was measured by weighing the bin after harvesting 2 beds of 1 plot for spring wheat/faba bean mixture and 1 bed of 1 plot for spring wheat. Sugar beet yield was measured using subsamples from a beet harvester.

4.2.11. STATISTICAL ANALYSIS

Mixed-effects model analysis was used to assess effects of tillage system (MP, NIT) on soil physical quality. Tillage system was included in the statistical model as fixed effect in all cases. In addition, depth in the soil profile (i.e., for aggregate stability, penetration resistance, SOM, and SOC) or date of sampling (i.e., for K_{fs}) was also included as fixed effect. For soil water retention all of tillage system, depth, and matric suction were included in the statistical model as fixed effects. Block was defined as the random effect in all cases. Fields (i.e., Org A, Org B, and Conv A) were analysed separately. For K_{fs} data taken at multiple dates a first-order autocorrelation structure was used for repeated measures. Soil water retention curve data from two NIT plots and one sample from MP in Org B were missing, and were therefore removed from the analyses. Computations for linear mixed-effects models and multiple means comparisons were performed using the nlme and lsmeans packages of R (Lenth, 2012; Pinheiro et al., 2012; R Core Team, 2012). The type I error rate (α) was set at 0.05 for all statistical tests. Penetration resistance and field-saturated hydraulic conductivity data were square root transformed to improve ANOVA model assumption fit.

4.3. RESULTS

4.3.1. EFFECT OF TILLAGE ON SOIL WATER RETENTION

Non-inversion tillage (NIT) did not affect soil water retention in Organic field A (Org A) ($P = 0.11$ for 0–5 cm and $P = 0.56$ for 10–15 cm), though NIT had a significantly higher volumetric water content at 1580 cm matric suction at 10–15 cm depth ($P < 0.01$) than mouldboard ploughing (MP) (Fig. 4.3). Non-inversion tillage increased soil water retention in Organic field B (Org B) at 0–5 cm depth ($P < 0.01$) between matric suctions 10 cm to 619 cm and at 10–15 cm ($P < 0.01$) between matric suction values of 10 cm to 15500 cm (Fig. 4.3). In no case did NIT increase volumetric water content at saturation (matric suction of 1 cm). Marginally significant effects ($P = 0.06$) were found in both Org A and Org B at saturation at soil surface (0–5 cm depth).

4.3.2. Effect of tillage on field-saturated hydraulic conductivity

Tillage significantly affected field-saturated hydraulic conductivity (K_{fs}) in statistical models in Org A ($P = 0.04$), Org B ($P < 0.01$), and Conv A ($P = 0.05$) (Table 4.2). MP had significantly higher K_{fs} than NIT in the measurements taken before crop harvest in autumn 2011 in Org A ($P < 0.01$) and in autumn 2012 in Org B ($P < 0.01$), and in autumn 2012 in Conv A after sugar beet harvest ($P < 0.01$).

4.3.3. Effect of tillage on soil water content

Soil water content (SWC) taken to 20 cm depth at the time of measuring other soil physical parameters was significantly higher in NIT than MP in Org A ($P < 0.01$) and Conv A ($P = 0.03$). However, SWC in Org B was marginally less in NIT than MP ($P = 0.09$) (Table 4.2).

4.3.4. Effect of tillage on aggregate stability

Non-inversion tillage increased mean weight diameter (MWD) aggregate stability at 10–20 cm below soil surface in Org A ($P < 0.01$), Org B ($P < 0.01$), and Conv A ($P < 0.01$)(Table 4.3). Only in Conv A, MWD was higher in NIT than MP at 0–10 cm ($P < 0.01$).

4.3.5. Effect of tillage on soil dry bulk density

There was no significant treatment effect on soil dry bulk density at any depth in Org A, though dry bulk density did vary significantly between depths ($P < 0.01$)(Table 4.3). Soil dry bulk density in Org B was significantly higher in NIT than MP 10–15 cm ($P = 0.05$).

4.3.6. Effect of tillage on penetration resistance

Soil penetration resistance (PR) was significantly higher in NIT than MP in both Org A from 17–39 cm soil depth ($P < 0.01$), Org B from 8–35 cm soil depth ($P < 0.01$), and Conv A from 7–35 cm soil depth ($P < 0.01$) (Table 4.2). In addition, PR in Org A was significantly higher in MP than NIT from soil surface down 6 cm.

4.3.7. EFFECT OF TILLAGE ON SOIL ORGANIC MATTER CONTENT AND CARBON STOCKS

Soil organic matter content (SOM) was significantly higher in NIT than MP at 0–10 cm of Org A ($P = 0.04$), Org B ($P < 0.01$), and Conv A ($P < 0.01$)(Table 4.3). SOM was also higher in NIT than MP at the 10–20 cm depths of Org B (marginally at $P = 0.07$) and Conv A ($P = 0.01$).

Soil organic carbon (SOC) stocks were assessed in autumn 2011 and spring 2012 after initiation of tillage trials in 2008. After adjusting for dry bulk density, SOC stocks in Org B NIT where higher at both 0–5 cm ($P < 0.01$) and 10–15 cm ($P < 0.01$) depths (Table 4.3). There was no difference in SOC stocks cumulative by profile in Org A but in Org B there was a marginally significant difference ($P = 0.07$) of 3.1 Mg ha^{-1} (± s.e. 0.36)(data not shown).

4.3.8. EFFECT OF TILLAGE ON CROP YIELD

Crop yield was higher in NIT than MP in Org A (wheat/faba bean mixture, $P < 0.01$), Org B (spring wheat), and Conv A (sugar beet)(Table 4.2). Effects were not significant in Org B or Conv A.

Table 4.2: Soil physical properties[1]

	K_{fs} (cm min^{-1})[2]						SWC (g kg^{-1})		Crop yield (Mg ha^{-1})	
	Spring 2011		Autumn 2011		Autumn 2011 b					
	MP	NIT	MP	NIT	MP	NIT	MP	NIT	MP	NIT
Org A	0.46	0.41	2.68	1.46*	1.60	1.92	217.44(4.50)	235.18(4.50)*	4.45(0.08)	5.06(0.08)*
	Spring 2012		Autumn 2012							
	MP	NIT	MP	NIT						
Org B	1.06	0.76	8.23	5.23*			189.93(1.97)	185.95(1.97)	5.95(0.19)	6.48(0.19)
Conv A	0.86	0.89	0.18	0.03*			172.63(1.54)	177.79(1.54)*	91.80(1.27)	91.98(1.27)

[1] Tillage systems were mouldboard ploughing (MP) and non-inversion tillage (NIT). Farming systems were organic (Org A and Org B) and conventional (Conv A). Properties presented are field-saturated hydraulic conductivity (K_{fs}), soil water content (SWC), and crop yield. Significant treatment effects between tillage systems are indicated by '*' where $P \leq 0.05$. [2] K_{fs} values are back-transformed means and therefore standard errors are not presented. K_{fs} measurements in autumn 2011 were taken before and after crop harvest and before mouldboard ploughing and non-inversion tillage operations.

4.4. DISCUSSION

4.4.1. SOIL PHYSICAL FUNCTIONS

Soil's ability to retain and allow water to infiltrate is determined by soil structure (i.e., pore-size distribution and interconnectedness), soil organic matter, and soil texture that affect retention at higher suctions in particular (Hillel, 1998; Reynolds et al., 2002). Soil organic carbon stocks positively correlate with soil water content at high suctions including wilting point (approximately 15500 cm suction) (Carter, 1992).

There was no difference in the soil water retention behaviour measured in autumn 2011 between non-inversion tillage (NIT) and mouldboard ploughing (MP) in Organic field A (Org A) at most suctions. Contrastingly, NIT increased soil water retention at all suctions except the highest (1580 and 15500) at 0–5 cm depth and all suctions except

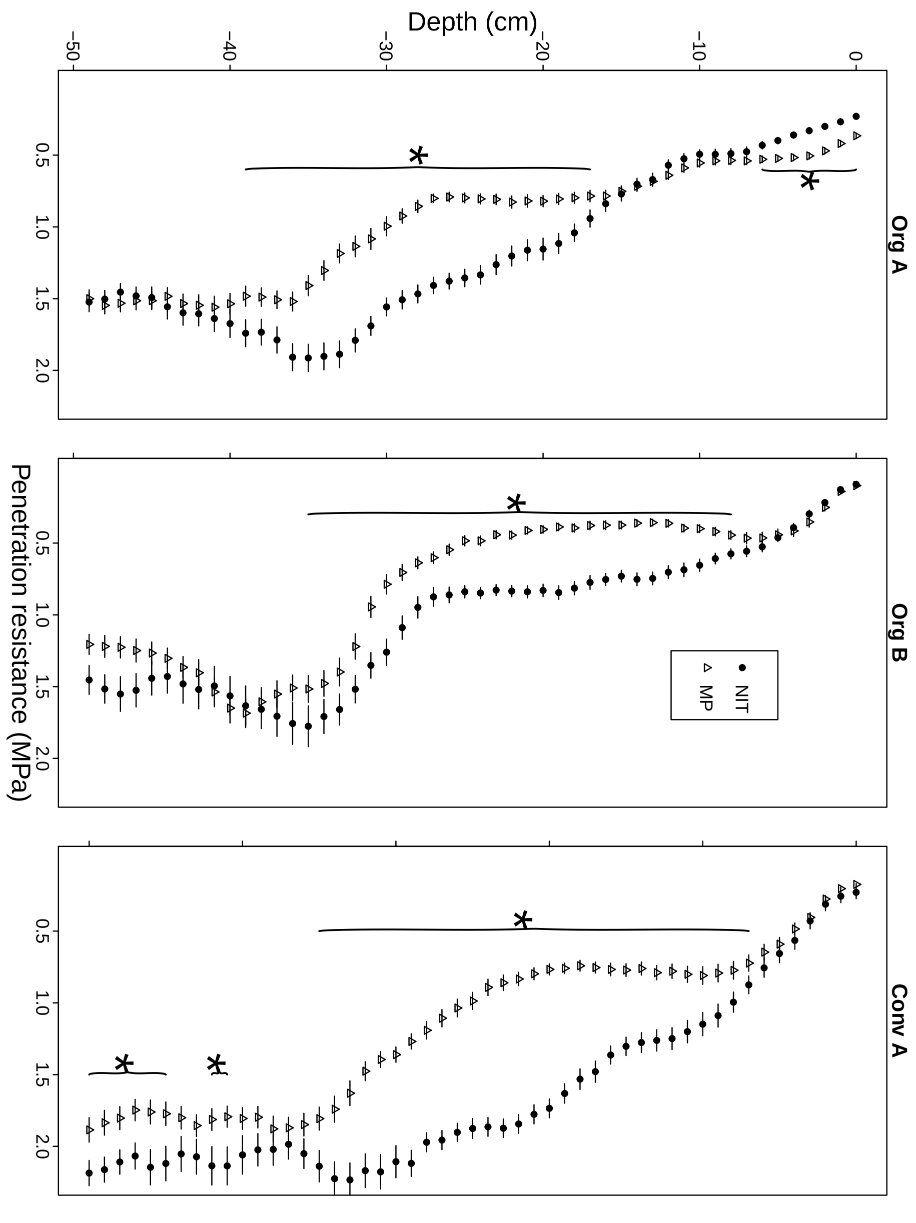

Figure 4.2: Penetration resistance in mouldboard ploughing (MP) and non-inversion tillage (NIT) under organic (Org A and Org B) and conventional (Conv A) farming. Horizontal lines indicate +/- standard error. Significant treatment differences are indicated by * where $P \leq 0.05$.

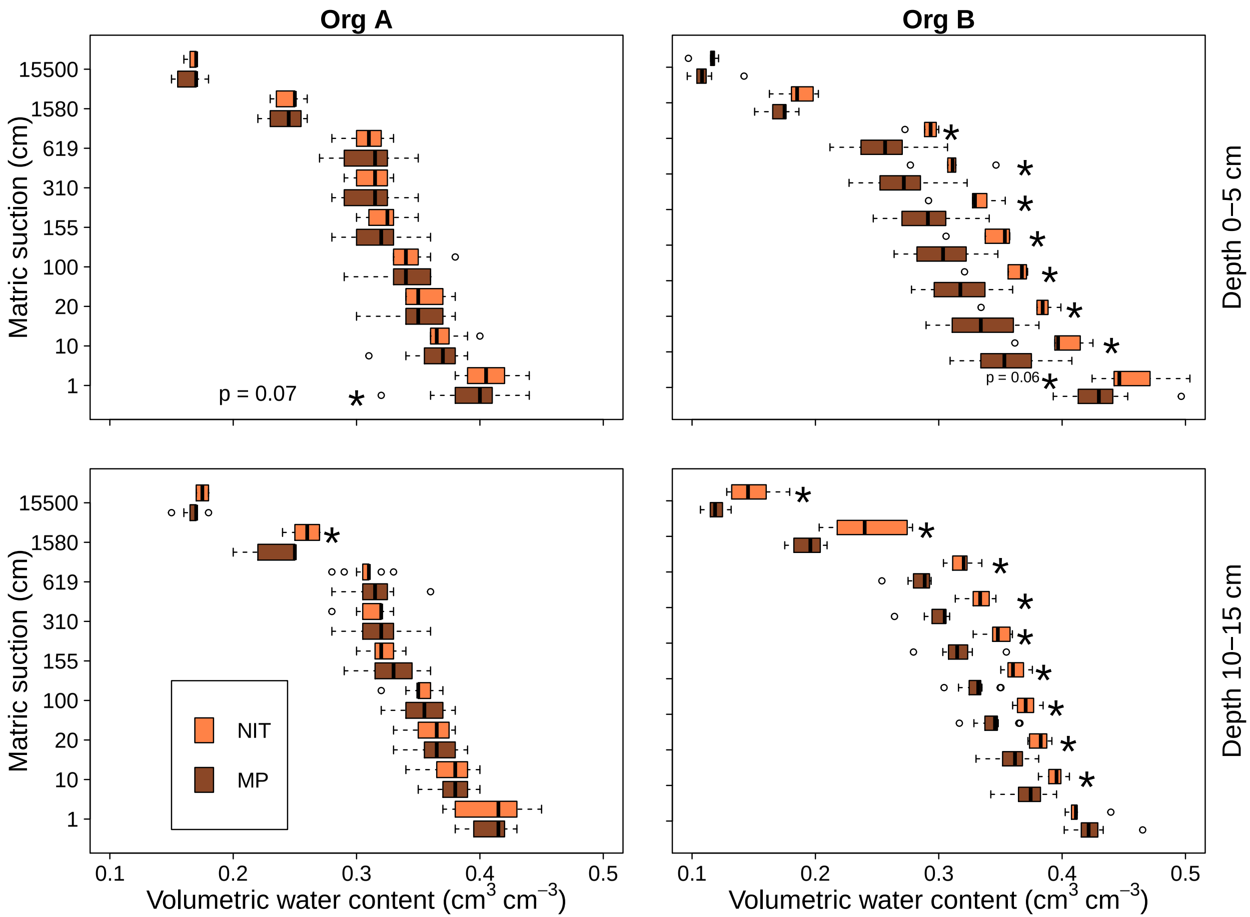

Figure 4.3: Soil water retention curves in mouldboard ploughing (MP) and non-inversion tillage (NIT) under organic farming (Org A and Org B). Significant treatment differences are indicated by * where $P \leq 0.05$ (unless indicated otherwise).

Table 4.3: Soil physical properties by depth in soil profile[1]

	Depth (cm)	Agg. stab. (mm)		SOM ($g kg^{-1}$)		Depth (cm)	BD ($g cm^{-3}$)		SOC ($Mg ha^{-1}$)	
		MP	NIT	MP	NIT		MP	NIT	MP	NIT
Org A	0-10	0.64(0.05)	0.65(0.05)	37.07(1.42)	40.69(1.42)*[2]	0-5	1.42(0.04)	1.40(0.04)	10.81(0.72)	11.72(0.72)
	10-20	0.50(0.05)	0.85(0.05)*	33.95(1.42)	32.74(1.42)	10-15	1.42(0.04)	1.47(0.04)	9.90(0.72)	9.84(0.72)
	20-30			30.52(1.42)	31.59(1.42)	20-30	1.59(0.04)	1.61(0.04)	19.91(0.72)	20.79(0.72)
	30-40			27.34(1.42)	25.30(1.42)	30-40	1.38(0.04)	1.33(0.04)	15.37(0.72)	13.75(0.72)
	40-50			24.35(1.42)	23.16(1.42)	40-50	1.17(0.04)	1.25(0.04)	11.68(0.72)	11.81(0.72)
Org B	0-10	0.57(0.05)	0.63(0.05)	35.94(0.80)	41.11(0.83)*	0-5	1.34(0.03)	1.29(0.04)	9.60(0.28)	10.86(0.41)*
	10-20	0.56(0.05)	0.75(0.05)*	34.22(0.80)	35.94(0.80)*[3]	10-15	1.42(0.03)	1.59(0.04)*	9.82(0.28)	11.65(0.37)*
Conv A	0-10	0.42(0.05)	0.64(0.05)*	28.47(0.44)	32.33(0.44)*					
	10-20	0.45(0.05)	0.71(0.05)*	29.59(0.44)	31.00(0.44)*					

[1] Tillage systems were mouldboard ploughing (MP) and non-inversion tillage (NIT). Farming systems were organic (Org A and Org B) and conventional (Conv A). Properties presented are soil aggregate stability (Agg. stab.), soil organic matter content (SOM), soil dry bulk density (BD), andsoil organic carbon stocks (SOC). Significant treatment effects between tillage systems are indicated by '*' where $P \leq 0.05$. [2] ($P = 0.08$) [3] ($P = 0.09$)

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saturation at 10–15 cm depth in Organic field B (Org B). This result suggests differences in soil structure, soil organic matter, and/or soil texture between tillage systems (Hillel, 1998; Reynolds et al., 2002). Similarly, reduced tillage featuring autumn chisel ploughing has been seen to increase the water holding capacity of topsoil (Hill et al., 1985). In a study conducted in Belgium under similar crop rotations (i.e., including wheat, potato, and sugar beet) and age of reduced tillage system (between 2–20 years), D'Haene et al. (2008) found that reduced tillage had lower dry bulk density, higher water content at saturation, but no difference in the water retention curve at 25–30 cm depth, higher mean weight diameter aggregate stability, and higher field-saturated hydraulic conductivity. Due to their proximity and homogeneity of the parent material, it seems unlikely that large spatial variation in inherent soil properties would exist between Org A and Org B (< 200 m distance between fields) that could account for differences in reactions to NIT in terms of soil water retention and dry bulk density and thus carbon stocks.

Field-saturated hydraulic conductivity (K_{fs}) was higher in MP than NIT in most autumn measurements but there was no difference between tillage systems in spring seasons. One objective of MP is to loosen soil to ease impedance of root growth by compact soil, and so this loose soil is able to transmit water faster than the denser NIT treatment, especially in autumn (pre-autumn MP) after the biological activity (e.g., plant roots and earthworms) has taken effect. There was quite some variation between the measurements taken in spring and autumn likely due to soil structural differences caused by crop root growth, soil biological activity, and shrink-swell action (Fuentes et al., 2004). All statistically significant effects were observed in autumn implying a seasonal effect of soil structure on K_{fs}. Soil hydraulic properties exhibit temporal variation due to the effects of wetting and drying cycles on soil pores (Bodner et al., 2013). Other studies on loamy soils in the Czech republic and western Germany found similar ranges of infiltration values (on average 1–1.5 cm min^{-1}) compared to our mean values (Kroulík et al., 2007; Vogeler et al., 2009). K_{fs} is known to be a highly variable parameter and therefore requires both spatial and temporal replication (Reynolds et al., 2002). High water infiltration rates in reduced tillage systems have mainly been measured when the systems have been in place for many years (Dao, 1993). Whereas short-term reduced tillage systems can decrease water infiltration compared to ploughed soils because of a lack of time for biological activity to affect soil structure (Lipiec et al., 2006; Matula, 2003). Water infiltration rates have also been found to be higher in reduced tillage systems, and in these cases the effect has been attributed to soil structural changes associated with accumulation of soil organic matter (Lal and Vandoren Jr, 1990; Shukla et al., 2003).

4.4.2. SOIL STRUCTURAL PARAMETERS

In the current study soil aggregate stability, soil penetration resistance, and soil dry bulk density were used as indicators of soil structure. Soil aggregate stability (mean-weight diameter (MWD)) was significantly higher at 10–20 cm depth in Org A, Org B, and Conv A. In addition, MWD was significantly higher at 0–10 cm depth in Conv A. Additional mechanical weeding operations in the organically managed fields may have destroyed aggregates in the top 10 cm. The lack of increase in aggregation in the top 10 cm is contrary to some findings in literature since crop residue retention at the surface generally increases aggregate formation (Hermawan and Bomke, 1997) and aggregate stability normally decreases with depth (Kay et al., 1994; Pulleman et al., 2003). Shallow cultivation to 8 cm depth in both MP and NIT may still cause too much disturbance to obtain a higher aggregate stability in NIT under organic farming.

Penetration resistance is considered a proxy for the ability of roots to grow through soil, and is known to be dependent on soil water content, soil texture, and soil dry bulk density. NIT increased soil penetration resistance in both Org A, Org B, and Conv A. Penetration resistance pressures were well below 3.6 MPa where root growth could cease (Ehlers et al., 1983), though NIT consistently had values greater than the 1 MPa that has been shown to reduce root growth by 50% (Stalham et al., 2007). Penetration resistance profiles remained similar despite being taken at distinct times (autumn 2011, spring 2012, and spring 2013 respectively) and in distinct crops (wheat/faba mixture, spring wheat, and sugar beet respectively). No difference in penetration resistance between tillage systems was seen in spring in Org B until 8 cm probably because spring cultivation to this depth equalised any differences. A similar study on a non-inversion tillage system using a subsoiler on an organically managed sandy loam soil in Denmark found an increase in penetration resistance similar to the current study (Munkholm et al., 2001).

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4.4.3. Soil organic matter and carbon stocks

Despite the short duration of the trial, NIT increased soil organic matter (SOM) relative to MP in the top layer (0–10 cm) of all fields measured. However, after adjusting for equivalent soil mass using dry bulk density and layer thickness, NIT increased soil organic carbon stocks (SOC) in Org B but not in Org A. Carbon stocks could not be calculated for Conv A because dry bulk density was not measured. The difference in effect of tillage system on soil carbon seen between Org A and Org B could be attributed to management of animal and green manures. Between 2009 and 2012 Org B received 61.4 Mg ha^{-1} more animal manure than Org A (data not shown). Furthermore, there was a ley year in Org B where the leguminous grass/clover mix was present for more than one calendar year. NIT affords a longer window of opportunity for cover crops in that they are not ploughed under in autumn as in the MP system and thus are present until killed by cold temperatures or spring cultivation. Increases in SOC in reduced tillage have also been noted in literature. Alvarez (2005) reviewed 161 experiments and found that in temperate climatic zones reduced tillage increased soil organic carbon content compared to conventional tillage systems by 9% in the 0–20 cm, 6% in the 0–30 cm and 3% in the 0–60 cm depth layers. The increase of SOC in reduced tillage may be limited to the top 3 to 5 cm depth, as was found in 0–10 cm but not below in Org A of the current study (Pinheiro et al., 2004; Tebrügge and Düring, 1999). A delay in achieving highest soil carbon sequestration rates after switching from ploughing to no-till or reduced tillage is expected, with peak sequestration 5 to 10 years after conversion (West and Post, 2002). Significant differences in soil carbon stocks were observed in the current study after 3-4 years in the top 15 cm of one field but not in the other and not below 15 cm.

4.4.4. Crop yield

A reduction in soil tillage intensity, like that used in NIT in the current study, may affect crop yield through adjustments to the soil physical, biological, and chemical environment as well as through altered weed and disease pressures. NIT significantly increased crop yield of wheat/faba mixture in Org A in 2011. There was no statistical difference between tillage systems in spring wheat in Org B in 2012 nor in sugar beet in Conv A in 2012, though NIT was higher on average. Discussion on the effects of reduced tillage on crop yields shows mixed results. Rasmussen (1999) noted that cereal yields were only slightly lowered and direct drilled potatoes can have higher yields in reduced tillage than ploughing systems, but that crop rotations require greater attention in order to control weed and disease problems. A meta-analysis of 47 studies in Europe showed results that contrast those presented in the current study (Van den Putte et al., 2010). Reduced tillage, excluding no-till, did not affect spring cereal or sugar beet yields, but winter cereal yields were reduced by 4% (Van den Putte et al., 2010). NIT may be a viable soil management strategy provided that timing of farm operations is improved resulting in fewer tractor passes and reduced fuel requirements (Morris et al., 2010). Minimising loss in crop yields should also be a consideration for adoption of new soil management practices such as organic farming, non-inversion tillage, or controlled-traffic farming.

4.5. CONCLUSIONS

Non-inversion tillage consistently lowered field-saturated hydraulic conductivity in both conventional and organic farming in autumn measurements. This consistency of effects in autumn, but lack of effect in spring, suggests that differences in field-saturated hydraulic conductivity between tillage systems developed within each growing season. Crop root growth and soil biological activity differences between tillage systems within growing seasons resulted in differential effects on macropore flow. Soil structural parameters including aggregate stability and penetration resistance were higher in non-inversion tillage than mouldboard ploughing in both organic and conventional farming. On the other hand, soil water retention and carbon stocks were improved by non-inversion tillage in one of two organically managed fields probably because of differences in organic inputs and cropping history. There was no difference in soil carbon stocks between tillage systems in the case where soil carbon was measured to 50 cm depth. Crop yield was improved by non-inversion tillage relative to mouldboard ploughing in the organic wheat/faba bean mixture, and there was no yield penalty in organic spring wheat or conventional sugar beet.

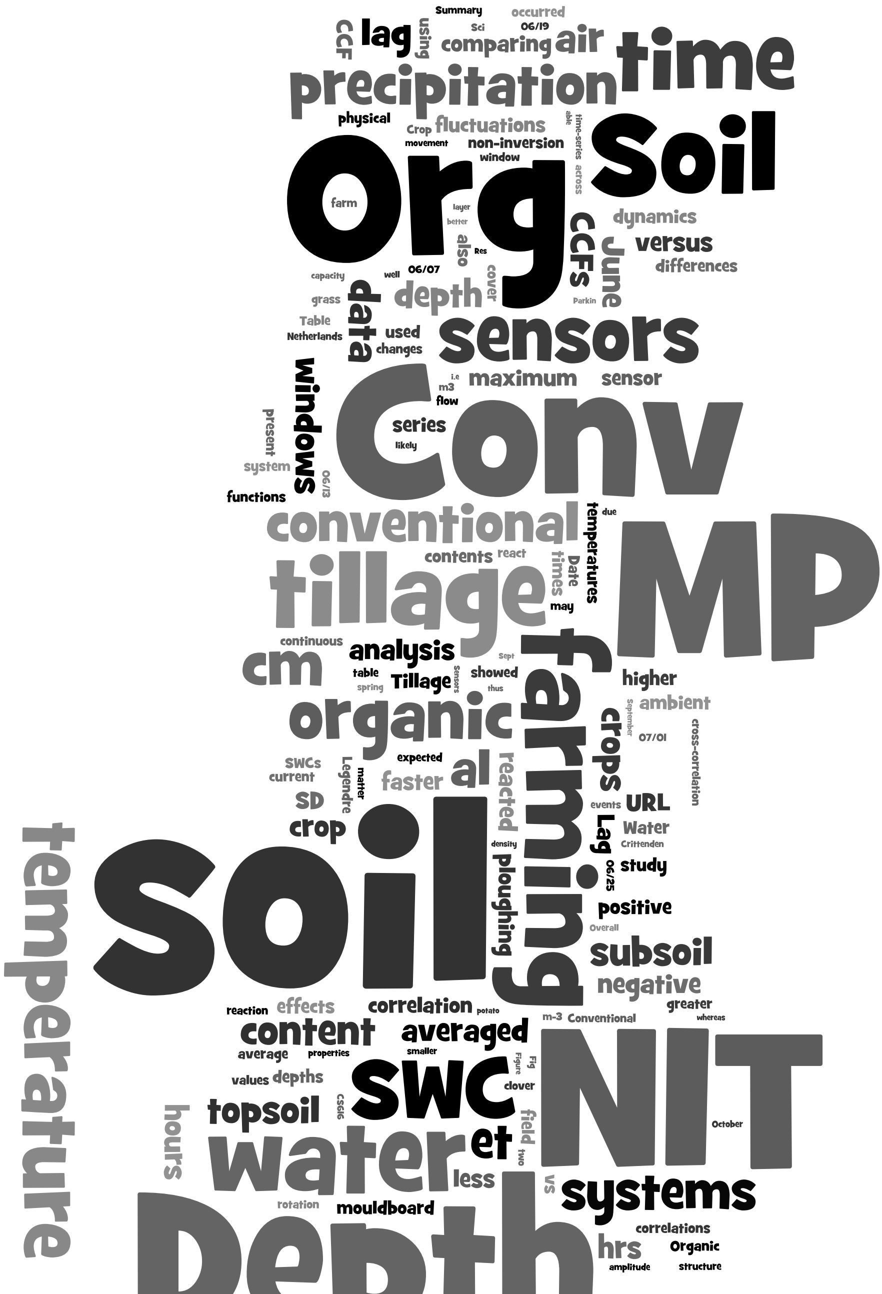
Non-inversion tillage, therefore, created a denser and more stable soil, that in the case of organic farming could improve water storage and sequester carbon depending on organic inputs, cropping history, or phase of crop rotation. Tillage system effects on soil structural parameters were consistent between crops and between farming systems. Additionally, it is noteworthy that effects on soil organic matter and soil carbon in particular could be observed after only 3-4 years of reduced tillage.

Reduced tillage intensity systems, such as non-inversion tillage, therefore have the capacity to improve soil physical quality in terms of soil structure and soil water storage in both organic and conventional farming. Increased soil density under reduced tillage can impede soil water transmission and can therefore be detrimental to crops sensitive to soil compaction. Overall, given the potential farm savings in labour and time costs by replacing mouldboard ploughing with reduced tillage and the improved soil physical quality, non-inversion tillage is a viable option for farmers.

5

SOIL WATER AND TEMPERATURE DYNAMICS IN CONTRASTING TILLAGE SYSTEMS UNDER CONVENTIONAL AND ORGANIC FARMING

This chapter has been submitted for peer-reviewed publication.



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Soil water and soil temperature control soil functions in agroecosystems such as nutrient cycling and greenhouse gas emissions, seed emergence and crop growth, as well as timing of soil management operations such as tillage, seeding, and harvesting. Reduced tillage relative to mouldboard ploughing and organic arable farming as compared to conventional arable farming may affect soil water and soil temperature regimes due to modifications in soil structure, soil cover, and soil organic matter content. The current study examined continuous soil water content (SWC) and soil temperature (soil T) data in mouldboard ploughing (MP) and non-inversion tillage under both conventional and organic farming. Conventional and organic farming systems were separate, but adjacent, field experiments run in parallel each with the same tillage treatments but different crop rotations. Crop rotations included both cereals and tuber crops, and soils were marine clay loam. SWC was collected at 0–21 cm and 80–101 cm depths and soil T was collected at 11 cm and 71 cm depth. SWC and soil T data were analysed using time-series analysis in four one-month time windows in 2012 and 2013 with hourly time steps. Monthly average SWCs were 0.32 ± 0.02 $m^3\ m^{-3}$ *in MP and* 0.41 ± 0.02 $m^3\ m^{-3}$ *in NIT at 0–21 cm, whereas SWCs were* 0.50 ± 0.01 $m^3\ m^{-3}$ *in MP and* 0.54 ± 0.01 $m^3\ m^{-3}$ *in NIT at 80–101 cm in conventional farming, averaged over all four time windows and crops. SWC at 0–21 cm in conventional farming displayed no reaction time difference between tillage systems, but SWC sensors in MP reacted 11 hrs faster than NIT at 80–101 cm, on average. In organic farming, average SWCs in MP was* 0.38 ± 0.01 $m^3\ m^{-3}$ *and* 0.37 ± 0.02 $m^3\ m^{-3}$ *in NIT at 0–21 cm, whereas SWCs were* 0.52 ± 0.01 $m^3\ m^{-3}$ *in MP and* 0.47 ± 0.01 $m^3\ m^{-3}$ *in NIT at 80–101 cm. In conventional farming, SWC reacted faster to precipitation (by 11 hrs) and soil T reacted faster to ambient air temperature changes (by 5 hrs) under mouldboard ploughing than under non-inversion tillage in subsoil. However, there was no tillage effect in topsoil in conventional farming. In organic farming, SWC reacted faster to precipitation in non-inversion tillage than mouldboard ploughing in both topsoil (by 1 hr) and subsoil (by 1 hr). Soil temperature under non-inversion tillage also reacted faster than mouldboard ploughing in topsoil (6 hrs), however the opposite was true in subsoil where soil under mouldboard ploughing reacted faster than non-inversion tillage (3 hrs), averaged over all time windows and crops, in organic farming. Therefore, differences in soil structure and soil organic matter content due to tillage system manifest themselves in differences in topsoil SWC and soil T dynamics in organic farming but not conventional farming. Spatial heterogeneity of preferential flow patterns became apparent through a mixture of positive and negative correlations between topsoil and subsoil sensors.*

5.1. INTRODUCTION

Water content and temperature regulate most physical, chemical, and biological processes in soil (Topp and Ferré, 2002). Soil water content influences soil trafficability and workability, thus affecting timing of tillage, planting, harvesting, and irrigation (Droogers et al., 1996; Schulte et al., 2012; Topp et al., 1997). Crop emergence and yield are also related to availability of soil water and soil temperature (Licht and Al-Kaisi, 2005). Therefore, soil water content (SWC) and soil temperature influence farm environmental and economic sustainability (Schulte et al., 2012).

Changes in soil tillage practises affect soil physical properties but subsequent effects on soil water and temperature regimes remain less clear. Conventional tillage incorporates crop residues and manures, controls weeds, and loosens top soil. Conventional tillage also destroys aggregates and compacts sub-soil thus reducing hydraulic conductivity and creating physical conditions that can have negative effects on plant roots and soil biota (Huwe, 2003). Soil becomes compacted beneath tires thus restricting permeability and movement of water and gases (Topp et al., 1997). Reductions in soil tillage intensity are aimed at lowering costs (e.g., labour, fuel) and increasing soil ecosystem function such as soil carbon sequestration and soil and water conservation, as well as soil biodiversity (El Titi, 2003; Holland, 2004; Morris et al., 2010). Reduced tillage can buffer water logging and drought extremes by improving soil structure and soil organic matter content, allowing for better drainage and water holding capacity (Holland, 2004).

Other farm management strategies may also impact soil water and temperature dynamics. Organic farming can influence soil structure and soil carbon, and therefore soil physical functions (Lotter et al., 2003; Pimentel et al., 2005). In organic farming neither pesticides nor synthetic fertilisers are allowed, and animal manures and larger and more diverse crop rotations (especially including legumes) are employed. Organic farming systems can perform better than conventional in both drought and extreme rainfall conditions due to better water holding capacity and infiltration rates (Lotter et al., 2003). Organic farming can have higher soil water supply capacity and higher crop yield than conventional farming, but may have higher susceptibility to soil compaction (Droogers and Bouma, 1996; Droogers et al., 1996). However, few studies that investigate tillage systems have done so in both conventional and organic farming (Seufert et al., 2012). Measurements of SWC and soil temperature, as well as soil physical functions such as water retention, hydraulic conductivity, and infiltration are generally done by collecting point-in-time data. Continuous measurements allow for more powerful and potentially meaningful insights to be drawn that reflect the dynamic nature of soil environmental conditions in the field.

Few studies that have used dielectric sensors to compare tillage system effects looked at soil water budgets, preferential flow and SWC and temperature during freeze-thaw processes (Kulasekera et al., 2011; McCoy et al., 2006; Parkin et al., 2013), but have often used only a small number of sensors or measurements in time (Fabrizzi et al., 2005; Licht and Al-Kaisi, 2005; Wu et al., 1997). Few, if any, studies have compared and contrasted SWC and temperature dynamics in tillage systems under conventional and organic farming at several depths as was done in the current study.

Reduced tillage systems generally have higher soil density than conventionally tilled soil because of lack of loosening from ploughing and natural reconsolidation. However, reduced tillage systems also maintain continuous macropores better than mouldboard ploughing systems since their continuity is not disrupted by ploughing. Soil water and temperature must move through this denser soil matrix in reduced tillage systems compared to conventional systems and therefore these movements would be expected to be slower in NIT than in MP. Organic farming systems generally have higher soil organic matter contents than conventional farming systems because of increased organic material inputs from manures and crop residues, and hence greater water holding capacity which could result in a buffering effect against precipitation and air temperature fluctuations. Macropores, whether biogenic or wet/dry cycling in origin, could facilitate downward movement of soil water and temperature. It was hypothesised that NIT would react slower and with smaller amplitude fluctuations to precipitation and air temperature changes than MP at and between surface and subsoil depths. Reactions to precipitation and air temperature fluctuations were expected to be less pronounced in organic farming than in conventional farming.

5.2. Materials and Methods

5.2.1. Site description

The study was carried out at PPO Lelystad research farm of Wageningen University and Research Centre ($52°32'N, 5°34'E$) between 2011 and 2013. PPO Lelystad is located in the province of Flevoland, The Netherlands, in a polder reclaimed in 1957. Soil at the farm is a calcareous marine clay loam with 23% clay, 12% silt and 66% sand on top of sandy clay layers that reach 100 cm depth. Tile drains were located at approximately 80 cm depth and spaced at 5 m. Groundwater levels averaged yearly reach 40–80 cm depth at their highest point and >120 cm at their lowest (Alterra, 2013). Soil at PPO Lelystad represents a large proportion of prime agricultural land in The Netherlands. Mean yearly precipitation is 825 mm and mean daily temperature is 10°C (Royal Netherlands Meteorological Institute, 2013).

5.2.2. Experimental design and farming practices

The study was conducted in two tillage experiments run in parallel in two adjacent fields separated by a ditch. Conventional farming (CONV) and organic farming (ORG) fields were 95 by 183 m, with 12 plots (3 treatments and 4 repetitions) within each field (Fig. 5.1). Individual plots measured 13 by 85 m split into 4 controlled traffic beds of 3.15 m. Treatments, arranged in randomised complete block designs (n=4), were mouldboard ploughing (MP), non-inversion tillage (NIT), and minimum tillage (M), though M was not included in the current study as practical implementation on farms is less likely.

MP, the standard primary tillage practise in the area, was done to 23–25 cm depth after harvest of the main crop and cover crop (if used) in autumn using a mouldboard plough. NIT was characterised by the use of a sub-soiler (Kongskilde Paragrubber Eco 3000) as primary tillage instrument in autumn instead of ploughing. In NIT soil is slightly lifted at 18–23 cm depth and soil is not inverted. Both NIT and MP plots were cultivated to 8 cm in spring and fall for seedbed preparation and superficial incorporation of crop residues before seeding of cover crop (if applicable) or main crop.

Conventional farming practices in CONV consisted of pesticide use, synthetic fertilizers, and mechanical and chemical weed control when necessary. Organic farming contained a longer crop rotation (6 compared to 4 yrs in CONV), animal manures, neither pesticides nor synthetic fertilizers, and mechanical and hand weeding. Crop rotation in CONV was onion/winter carrot, potato, sugarbeet, winter wheat/spring barley whereas crop rotation in ORG was pea, potato, grass/clover mix, cabbage, spring wheat, and winter carrot (Tables 5.1 and 5.2). Cover crops were sown after main crop harvest where time and soil conditions allowed. Cover crops were present for longer durations in NIT because the sub-soiling itself does not destroy the cover crop, whereas in MP the cover crops are ploughed under.

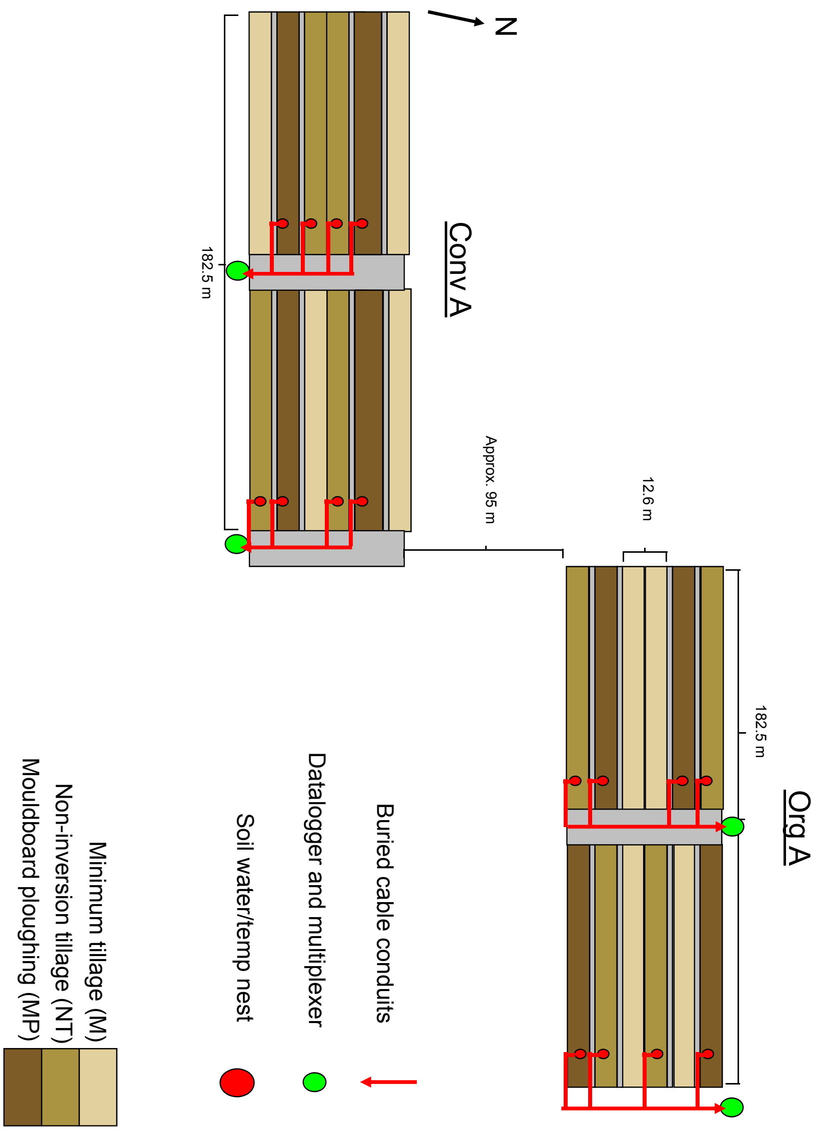

Figure 5.1: Plot plan including locations of sensor nests and buried cables connecting to dataloggers

Table 5.1: Crop rotation in Conventional field A (cover crop/green manure)

Year	Crop in CONV (cover crop)	Tillage date	Seeding date	Harvest date
2009	Spring barley	MP: 02/12/2008 NIT: 10/01/2009	02/04/2009	29/07/2009
	(Italian rye grass)		12/08/2009	
2010	Onion	MP: 20/11/2009	26/04/2010	12/10/2010 and 01/11/2010
2011	Potato	MP: 12/11/2010 NIT: 01/11/2010 (MP as well)	11/04/2011	17/8/2011
	(rye grass)		20/08/2011	
2012	Sugar beet	06/10/2011 NIT: 16/11/20011	28/03/2012	13/10/2012
2013	Spring barley (yellow mustard/fetch/facelia)	MP: 15/11/2012	03/04/2013 16/08/2013	09/06/2013

Table 5.2: Crop rotation in Organic field A (cover crop/green manure)[1]

Year	Crop in ORG (cover crop)	Tillage date	Seeding date (both MP and NIT)	Harvest date
2009	Spring wheat	MP: 8/12/2008 NIT: 27/12/2008	03/04/2009	10/08/2009
	(white clover)		4/6/2009	
2010	Carrot	MP: 20/11/2009	26/05/2010	15/10/2010
2011	Spring wheat/ faba bean mixture	MP: 11/11/2010 NIT: 18/10/2010 (cultivator - subsoiled, MP as well)	25/03/2011	1-9-2011
	(yellow mustard)		6/9/2011	
2012	Potato		02/05/2012	13/08/2012
	(grass clover)		31/08/2012	
2013	Grass clover (grass clover)			22/05/2013, 08/07/2013, 22/08/2013, 07/10/2013

[1] Organic farming has a 6 year crop rotation (5 shown).

5.2.3. SENSORS AND SENSOR INSTALLATION

An automated continuous SWC and soil temperature sensing system was installed in CONV during summer 2011 and in ORG during autumn 2010. Each sensor nest location (Fig 5.1) contained 4 SWC sensors (CS616 Water Content Reflectometer) and 3 temperature sensors (107 thermocouple; Campbell Scientific, Logan, UT, USA). A total of 64 SWC and 48 temperature sensors were installed in 2 fields (CONV and ORG) x 2 tillage treatments (MP and NIT) x 4 blocks x 4 depths (temperature sensors only at 3 depths).

Sensors were located 5 m inside the eastern edge of plots to avoid plot edge effects (Fig. 5.1). SWC sensors were inserted into the north vertical wall of a 5 m trench, and were angled downwards at 45° to be able to estimate water contents over soil layers and to minimise water movement along the sensor rods. SWC sensors were placed starting at 0 cm (Depth A), 35 cm (Depth B), 60 cm (Depth C), and 80 cm (Depth D). Surface sensors (Depth A + B) were removed for farm operations (i.e., ploughing, planting, and weeding) and reinstalled afterwards. Surface sensors were installed vertically (90° to soil surface) into ridges when the main crop was potato or carrot to ensure the sensors' areas of sensitivity were entirely within the soil volume, similar to Carter et al. (2005). Temperature sensors were installed horizontally at the centre of the vertical height of the SWC sensors (i.e., approx. 11 cm below the insertion point) to represent the mean temperature for that soil layer (Depth A, B, and C, respectively). Temperature sensors were placed at least 25 cm away from the SWC sensors to avoid signal interference.

Cables leading away from each sensor nest were placed in protective conduit pipe leading to plot edge then perpendicularly to field edge where data were collected using CR800 data loggers. Data loggers were powered with 10 W solar panels charging 12 V batteries and mounted on poles 1.5 m above the soil surface. Measurements were taken every 60 seconds and averaged to 30 minute intervals automatically by the dataloggers. Data were downloaded automatically from the in-field data loggers to a central computer at Wageningen University.

5.2.4. Sensor calibration

Site-specific sensor calibration is recommended per soil type (Kulasekera et al., 2011; McCoy et al., 2006; Seyfried and Murdock, 2001). For the current study, calibration per sensor was deemed too time consuming and costly. CS616 sensor data was calibrated for each layer of soil sensed by SWC sensors at PPO Lelystad. Soil was taken from a minimum tillage plot under conventional farming to conduct the calibration and soil for dry bulk density was measured in two locations 50 cm apart in each layer (A,B,C,D). Soil dry bulk densities (BD) were 1.47 g cm^{-3} in Depth A, 1.42 g cm^{-3} in Depth B, 1.24 g cm^{-3} in Depth C, and 1.46 g cm^{-3} in Depth D. One calibration was done for each soil layer using a methodology similar to Te Brake et al. (2012). Soil was dried at 105°C for 24 hours and ground (3 mm). Soil was then repacked into 12 cm diameter x 45 cm long PVC pipes to the mean BD for each layer. Pipes were then placed horizontally on a digital scale connected to a CR1000 datalogger. The repacked soil was wet to saturation and weights were recorded as the soil dried by evaporation. Polynomial equations were then fit to the data for each soil layer, and were then used to convert raw sensor output to volumetric water contents (Fig. 5.2). Depth B crosses the dense plough pan and hence output periods are elongated.

5.2.5. Statistical analysis

Time-series analysis was chosen to investigate tillage system differences in conventional and organic farming instead of applying a physical model that would have required the use of more measured physical parameters than were available. Raw signals from the dataloggers were converted to SWCs using the calculated calibration curves. Data from malfunctioning sensors was removed by excluding unrealistic values (i.e., values >100 or ≤ 0.05 for soil water contents and <-5 for soil temperatures) and unrealistic series (i.e., removal by visual assessment of 'jagged' behaviour). Of the individual sensor by time window and treatment combinations 18 of 128 water content time series and 27 of 128 soil temperature time series were excluded due to sensor malfunction or damage. Summary data presented here were averaged over these missing values. Time series techniques were then applied, a linear moving average filter with a 12 hour window was used to smooth out large jumps in the signal, and time series cross-correlation functions were created to investigate differences in peak lag times (not magnitude of the auto-correlations as peak lag times better address the hypotheses). Comparisons were made between the top and bottom sensor (Depth A vs Depth D (SWC) or Depth C

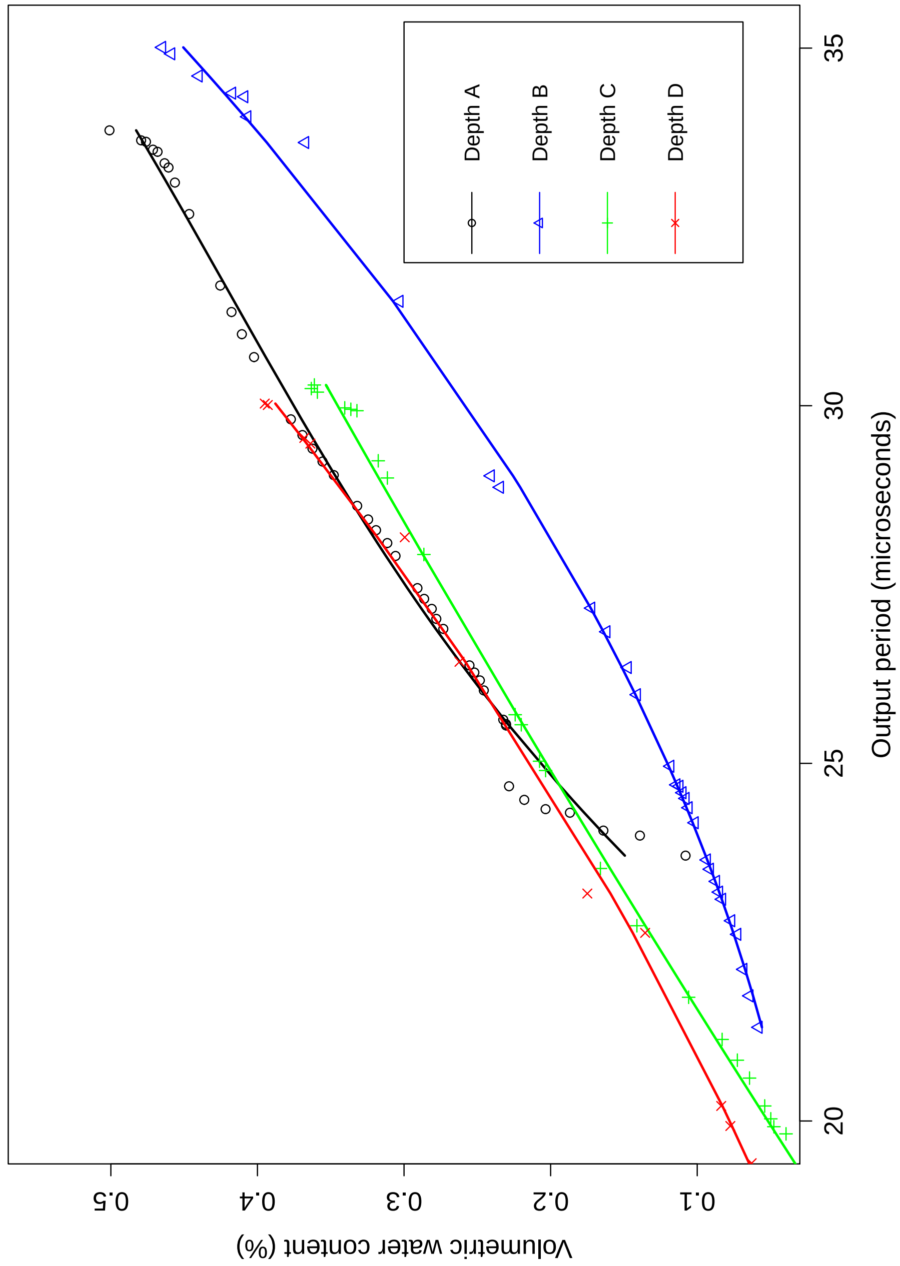

Figure 5.2: Calibration curves for CS616 soil water content sensors. Sensors were placed starting at 0 cm (Depth A), 35 cm (Depth B), 60 cm (Depth C), and 80 cm (Depth D) and angled downwards at 45°.

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(temperature) and between precipitation/ambient air temperature and the top/bottom sensor to test the hypotheses that reaction times would be slower in NIT and especially in conventional farming. Sensors at Depth A and Depth D/C were selected for analysis to represent topsoil and subsoil conditions and water entry and exit points of the system. Time series were segmented into periods representing early plant growth and the pre-harvest stage (depending on crop) to attain greater definition in results. Available time windows where all sensors were in the ground in both conventional and organic farming was limited by the timing and frequency of farm management practises (i.e., tillage, seeding, and weeding). Time windows selected were June 2012 (CONV had sugar beet, ORG had potato), Sept. 2012 (CONV had sugar beet, ORG had grass clover), June 2013 (CONV had spring barley, ORG had grass clover), and Oct. 2013 (CONV had yellow mustard/fetch/facelia, ORG had grass clover). All statistical computations were performed using R (R Core Team, 2012).

The cross-correlation function (CCF) describes changes in the coefficient of correlation between two time series x and y at time s and t with a changing time lag between them (Yule, 1921). Therefore, the CCF allows the lag corresponding to the highest correlation to be determined from the time scale. The CCF ρ was calculated as given in equation 5.1 from Shumway and Stoffer (2011), where γ represents autocovariance, and μ represents the mean function.

5

$$\rho_{xy}(s,t) = \frac{\gamma_{xy}(s,t)}{\sqrt{\gamma_x(s,s)\gamma_y(t,t)}} \tag{5.1}$$

$$\gamma_{xy}(s,t) = cov(x_s, y_t) = E[(x_s - \mu_{xs})(y_t - \mu_{yt})] \tag{5.2}$$

Cross-correlation can be used when the target variable (y) is expected to respond to an explanatory variable (x) at some unknown previous time (Legendre and Legendre, 2012). The time lag (delay) where maximum correlation occurs between explanatory and target variables can be identified using cross-correlation (Legendre and Legendre, 2012). Cross-correlation values range from −1 (negative correlation), to close to 0 (no correlation), to +1 (positive correlation). Precipitation, air temperature, and SWC or soil T (all hourly) in Depth A were used as x in the CCFs. SWC and soil T at Depth A and Depth D were used a y. Negative lag times mean that x leads y (e.g., precipitation leads reaction in SWC at Depth A), and positive lag times are excluded from the current analysis. Since the influence of precipitation and changes in ambient air temperature on SWC and soil T are of interest, and not the reverse as they are physically impossible, only negative lag times are considered. A maximum time lag of 96 hrs was chosen to ensure sufficient time for effects to appear.

5.3. Results

5.3.1. Soil water contents in tillage and farming systems

The months of June 2012 and October 2013 received more precipitation overall than did September 2012 and June 2013. This is reflected in the time series graphs showing June 2012 and October 2013 fluctuating in response to precipitation to a greater degree than September 2012 and June 2013 (Figures 5.3, 5.4, 5.5, and 5.6). Conventional farming

(CONV) mouldboard ploughing (MP) Depth A (0–21.2 cm depth) appears to respond with greater amplitude and appears able to respond to smaller precipitation events than do non-inversion tillage (NIT) or either tillage system in organic farming (ORG).

Relatively large precipitation events were required for both soil water sensors at Depth A and Depth D (80–101.2 cm depth) to react. In Sept. 2012 and June 2013 no precipitation event occurred that was sufficient for sensors at both Depth A and Depth D to react (Figures 5.3, 5.4, 5.5, and 5.6). In June 2012 Depth D CONV MP reacted more to precipitation events than all other treatments. In Oct 2013 two precipitation events over 20 mm per day occurred and sensors at both Depth A and Depth D in all tillage and farming systems reacted. Two CONV sensors continued to react to subsequent precipitation events (1 NIT and 1 MP), also some sensors in ORG responded and others did not irrespective of tillage system.

To compliment the time-series analyses used soil water content (SWC) and soil temperature (T) data were summarised by averaging over each individual time window as well as over all time windows and crops.

Table 5.3: Summary table of soil volumetric water contents averaged over time window and sensors [1]

	Depth A								Depth D							
	CONV				ORG				CONV				ORG			
	MP		NIT		MP		NIT		MP		NIT		MP		NIT	
	SWC	SD	SWC	SD	SWC	SD	SWC	SD	SWC	SD	SWC	SD	SWC	SD	SWC	SD
June 2012	0.35	0.02	0.42	0.02	0.40	0.02	0.39	0.02	0.52	0.01	0.57	0.00	0.53	0.00	0.48	0.00
September 2012	0.29	0.02	0.36	0.01	0.39	0.01	0.37	0.01	0.48	0.00	0.58	0.00	0.56	0.00	0.48	0.00
June 2013	0.32	0.02	0.39	0.01	0.35	0.01	0.36	0.02	0.50	0.00	0.51	0.00	0.53	0.01	0.47	0.00
October 2013	0.33	0.04	0.44	0.02	0.39	0.02	0.38	0.03	0.51	0.02	0.53	0.02	0.48	0.02	0.44	0.02
Overall average	0.32	0.02	0.41	0.02	0.38	0.01	0.37	0.02	0.50	0.01	0.54	0.01	0.52	0.01	0.47	0.01

[1] Soil water content (SWC, ($m^3\,m^{-3}$)) was measured at 0–21 cm depth (Depth A) and 80–101 cm depth (Depth D) in mouldboard ploughing (MP) and non-inversion tillage (NIT) systems in conventional (CONV) and organic (ORG) farming. Different crops were present in CONV and ORG during each time window. Standard deviation (SD) of the time series is also presented.

Table 5.4: Summary table of maximum lag values from cross-correlation functions comparing precipitation and soil water contents at Depth A and Depth D [1]

	Precip. vs Depth A				Depth A vs Depth D				Precip. vs Depth D			
	CONV		ORG		CONV		ORG		CONV		ORG	
	MP	NIT	MP	NIT	MP	NIT	MP	NIT	MP	NIT	MP	NIT
June 2012	-3.00	-3.67	-71.50	-64.75	-63.00	-67.33	-96.00	-96.00	-49.50	-76.50	-40.75	-54.75
September 2012	-23.50	-21.00	-26.25	-26.50	-92.50	-96.00	-54.75	-33.50	-33.00	-40.50	0.00	-3.00
June 2013	-10.33	-10.00	-43.00	-24.00	-49.00	0.00	-24.00	-48.00	-41.25	-52.00	-10.33	-9.75
October 2013	-2.67	-3.33	-5.00	-6.50	-3.33	-2.00	-18.75	-0.50	-6.50	-4.50	-29.75	-16.25
Overall average	-9.20	-9.50	-36.44	-35.50	-46.80	-41.33	-48.38	-51.25	-32.56	-43.15	-22.36	-20.94

[1] Cross-correlation functions were used to identify the time lag (delay) that maximised correlation between precipitation and soil water content (SWC) at Depth A (0–21 cm), SWC at Depth A and Depth D (80–101 cm), and precipitation and SWC at Depth D (Legendre and Legendre, 2012). Negative lag times represent the time (hours) shift between precipitation (or SWC at Depth A) and reaction in sensors at Depth A or Depth D. SWCs were monitored in mouldboard ploughing (MP) and non-inversion tillage (NIT) within conventional (CONV) and organic (ORG) farming. Different crops were present between CONV and ORG in each time window. Overall averages include all sensors with data from broken sensors and erroneous data omitted. Maximum lag was set at -96 hrs therefore values of -96 hrs should be read as $\leq$ -96.

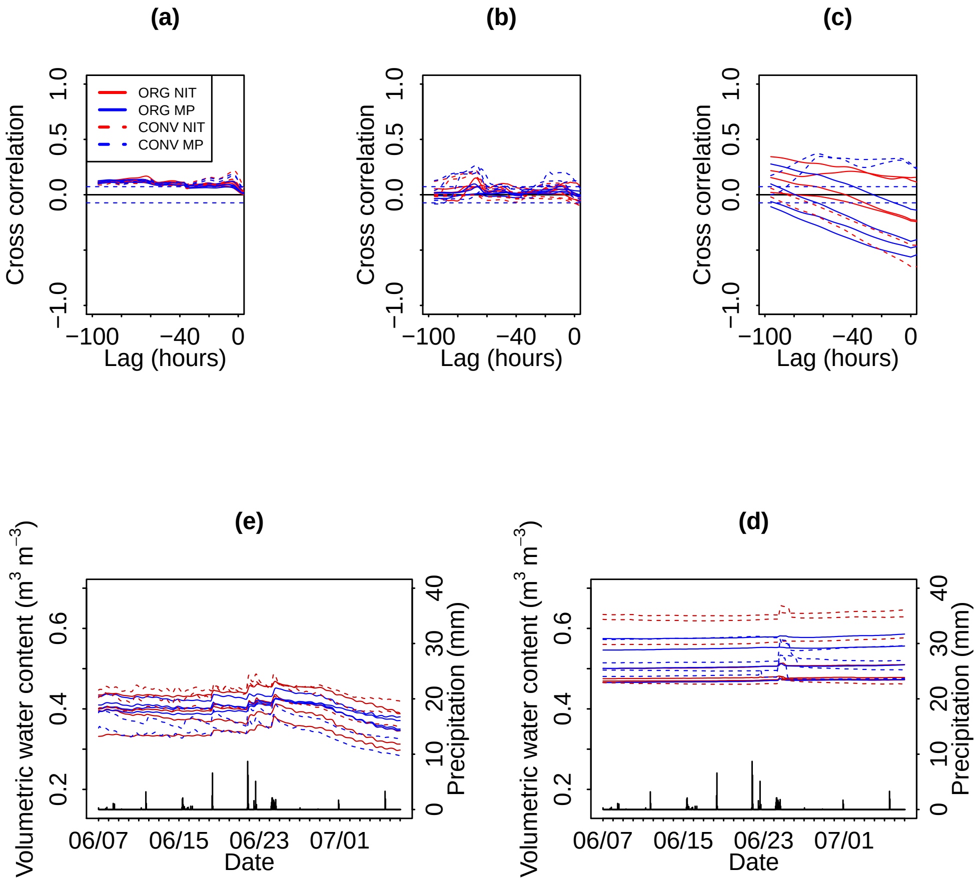


Figure 5.3: Soil water content and cross-correlation function plots for June 2012 (96 hour lag max). Volumetric water content (VWC, ($m^3\,m^{-3}$)) was measured at 0–21 cm depth (Depth A) and 80–101 cm depth (Depth D) in mouldboard ploughing (MP) and non-inversion tillage (NIT) systems in conventional (CONV) and organic (ORG) farming. Different crops were present in CONV and ORG during each time window. Cross-correlation functions presented are (a) precipitation versus SWC at Depth A, (b) SWC at Depth A versus SWC at Depth D, and (c) precipitation versus SWC at Depth D. Precipitation and SWC at Depth A (d) and precipitation and SWC at Depth D (e) are also displayed. Correlations within black dashed horizontal lines on cross-correlation plots indicate non-significance.

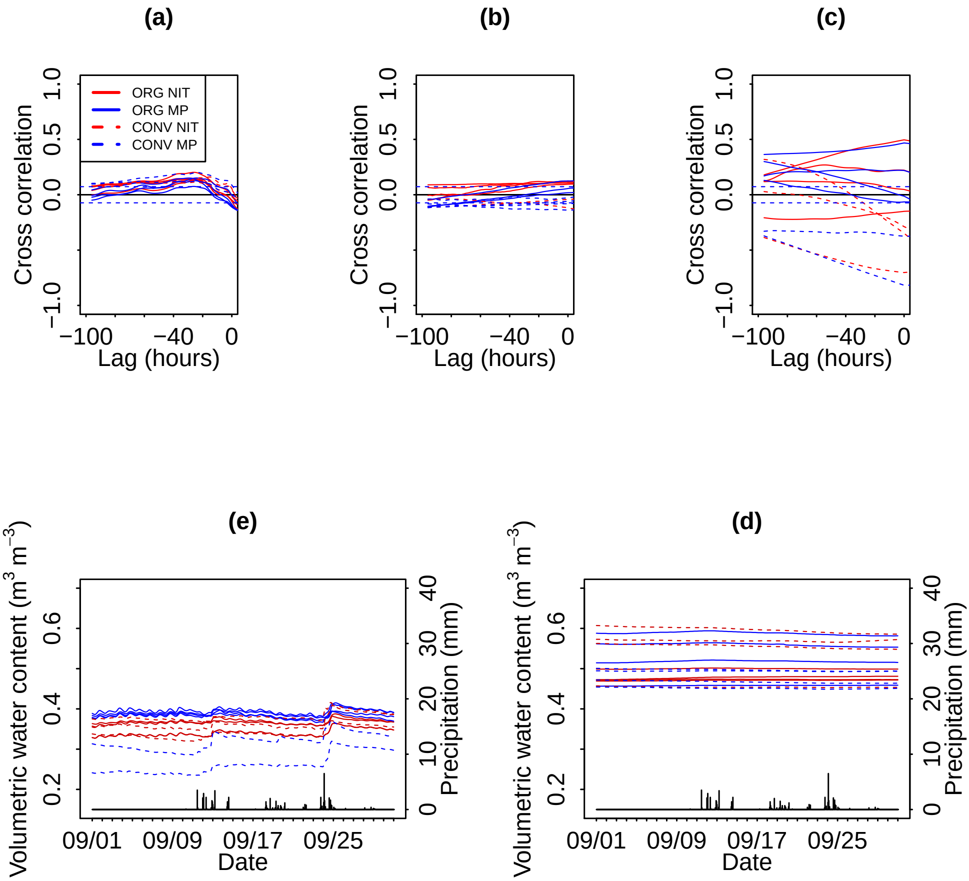


Figure 5.4: Soil water content and cross-correlation function plots for September 2012 (96 hour lag max). Volumetric water content (VWC, ($m^3\,m^{-3}$)) was measured at 0–21 cm depth (Depth A) and 80–101 cm depth (Depth D) in mouldboard ploughing (MP) and non-inversion tillage (NIT) systems in conventional (CONV) and organic (ORG) farming. Different crops were present in CONV and ORG during each time window. Cross-correlation functions presented are (a) precipitation versus SWC at Depth A, (b) SWC at Depth A versus SWC at Depth D, and (c) precipitation versus SWC at Depth D. Precipitation and SWC at Depth A (d) and precipitation and SWC at Depth D (e) are also displayed. Correlations within black dashed horizontal lines on cross-correlation plots indicate non-significance.

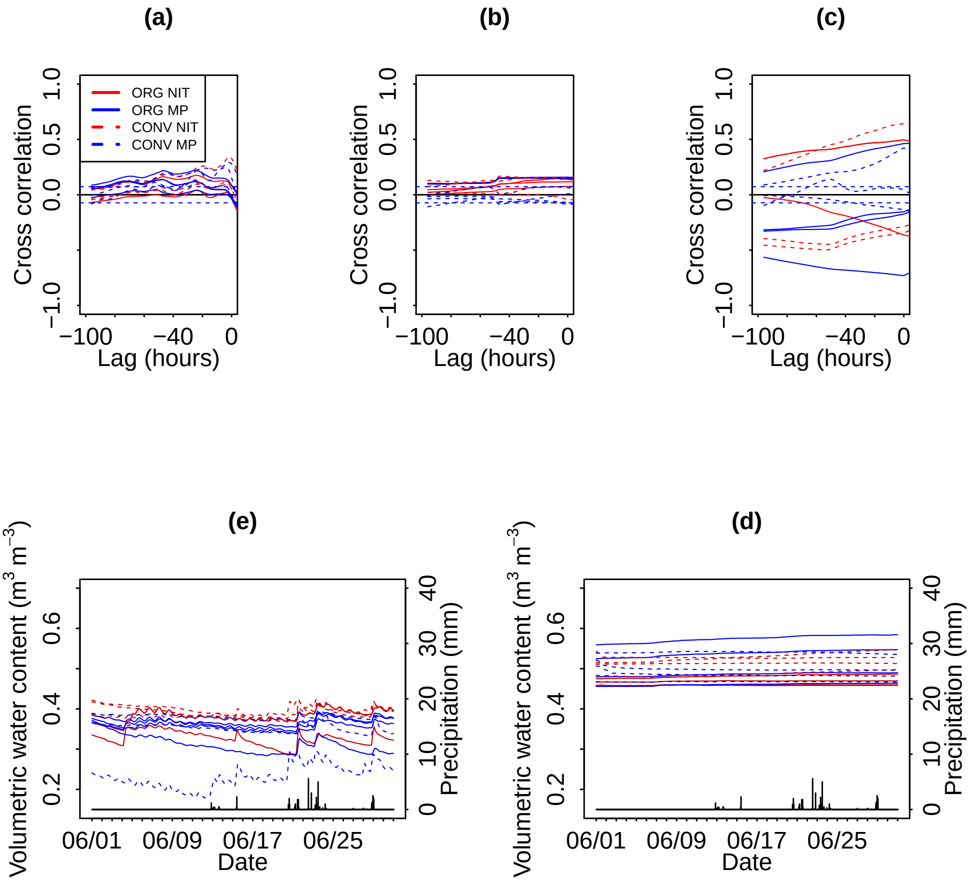


Figure 5.5: Soil water content and cross-correlation function plots for June 2013 (96 hour lag max). Volumetric water content (VWC, ($m^3\,m^{-3}$)) was measured at 0–21 cm depth (Depth A) and 80–101 cm depth (Depth D) in mouldboard ploughing (MP) and non-inversion tillage (NIT) systems in conventional (CONV) and organic (ORG) farming. Different crops were present in CONV and ORG during each time window. Cross-correlation functions presented are (a) precipitation versus SWC at Depth A, (b) SWC at Depth A versus SWC at Depth D, and (c) precipitation versus SWC at Depth D. Precipitation and SWC at Depth A (d) and precipitation and SWC at Depth D (e) are also displayed. Correlations within black dashed horizontal lines on cross-correlation plots indicate non-significance.

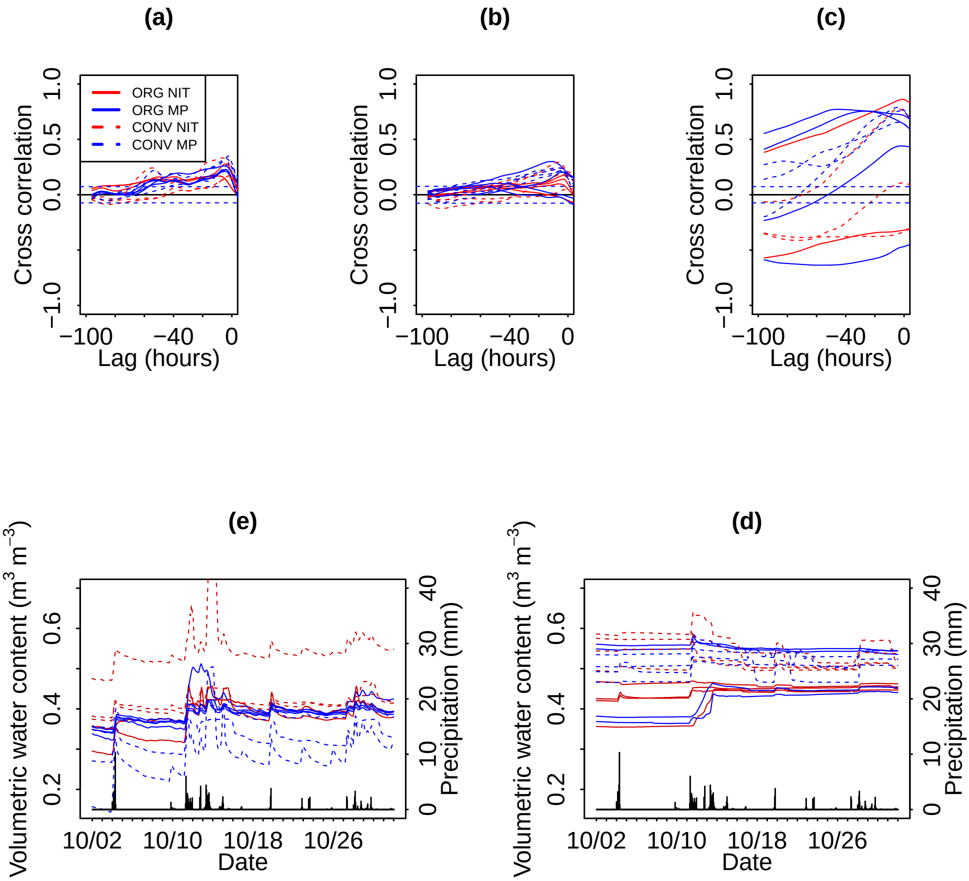


Figure 5.6: Soil water content and cross-correlation function plots for October 2013 (96 hour lag max). Volumetric water content (VWC, ($m^3\,m^{-3}$)) was measured at 0–21 cm depth (Depth A) and 80–101 cm depth (Depth D) in mouldboard ploughing (MP) and non-inversion tillage (NIT) systems in conventional (CONV) and organic (ORG) farming. Different crops were present in CONV and ORG during each time window. Cross-correlation functions presented are (a) precipitation versus SWC at Depth A, (b) SWC at Depth A versus SWC at Depth D, and (c) precipitation versus SWC at Depth D. Precipitation and SWC at Depth A (d) and precipitation and SWC at Depth D (e) are also displayed. Correlations within black dashed horizontal lines on cross-correlation plots indicate non-significance.

Tillage system effects on soil water contents in conventional farming

Highest SWC values, averaged across time windows and crops, were found in CONV under NIT at both Depth A (0.41 ± 0.02 $m^3\,m^{-3}$) compared to MP (0.32 ± 0.02 $m^3\,m^{-3}$) and Depth D (0.54 ± 0.01 $m^3\,m^{-3}$) compared to MP (0.50 ± 0.01 $m^3\,m^{-3}$) (Table 5.3). Cross-correlation functions (CCFs) of precipitation and SWC at Depth A showed no consistent tillage system differences in conventional farming (Figures 5.3, 5.4, 5.5, and 5.6 and Table 5.4). However, the CCFs of SWCs at Depth A versus SWCs at Depth D showed that NIT had maximum correlations at lag times 5.5 hrs less negative (faster reaction) than MP, averaged across all time windows. CCFs of precipitation versus SWCs at Depth D in conventional farming showed that MP had maximum correlations at lag times that were 10.6 hrs less negative than NIT. No clear patterns emerge from CCFs of soil water content sensor data at Depth A versus Depth D in either farming system because a mix of positive and negative correlations. In the two cases where little precipitation occurred (Sept. 2012 and June 2013) CCFs showed some positive and some negative correlations, whereas in June 2012 and Oct 2013 most correlations were positive, though CCFs were not significant.

Tillage effects on soil water contents in organic farming

ORG MP had higher SWC at Depth A (0.38 ± 0.01 $m^3\,m^{-3}$) than NIT (0.37 ± 0.02 $m^3\,m^{-3}$) and Depth D (0.52 ± 0.01 $m^3\,m^{-3}$) was higher than NIT (0.47 ± 0.01 $m^3\,m^{-3}$) averaged across all windows and crops (Table 5.3). NIT had maximum correlations at lag times less negative than MP in CCFs of precipitation versus SWC by 1.0 hrs at Depth A and by 1.4 hrs at Depth D. CCFs of SWCs at Depth A versus Depth D were had maximum correlations and less negative lag times in MP than NIT by 2.9 hrs.

Farming system effects on soil water contents

ORG appears to react with smaller amplitude fluctuations to precipitation events than CONV, in general (Figures 5.3, 5.4, 5.5, and 5.6). Conventional farming had maximum correlations at lag times that were 24.5 hrs less negative than organic farming in CCFs comparing precipitation versus SWC at Depth A. In CCFs comparing precipitation versus SWCs at Depth D organic farming was 16.9 hrs less negative than conventional farming averaged across all time windows investigated and crops present during those windows.

5.3.2. Soil temperature in tillage and farming systems

Tillage system effects on soil temperatures in conventional farming

Soil T sensor data averaged over all time windows and crops in conventional farming showed that the warmest treatment was CONV MP (14.72 ± 1.69°C) followed by CONV NIT (14.14 ± 1.61°C) at Depth A (11 cm depth) (Table 5.5). Similarly, at Depth C (71 cm depth) CONV MP (13.80 ± 0.71°C), and CONV NIT (13.77 ± 0.70°C) averaged over all time windows and crops. CCFs comparing ambient air temperature and soil T at Depth A in CONV showed inconsistent tillage effects across time windows and crops therein. Averaged over all time windows and crops, the lag time where maximum positive correlation occurred was less negative in MP than NIT by 3.0 hrs in the CCF comparing soil T at Depth A and soil T at Depth C in CONV. Contrastingly, the lag time where maximum positive correlation occurred in NIT was less negative than MP by 4.8 hrs in the CCF comparing ambient air T and soil T at Depth C in CONV.

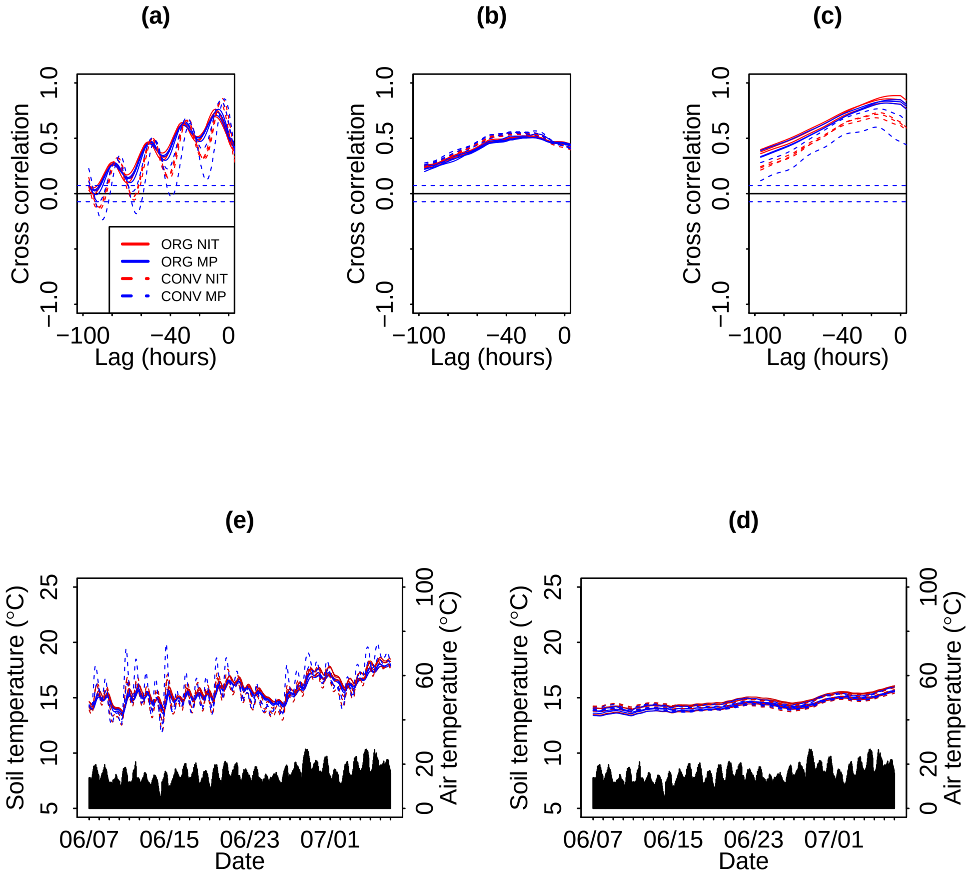


Figure 5.7: Soil temperature and cross-correlation function plots for June 2012 (96 hour lag max). Soil temperature (T) was measured at 11 cm depth (Depth A) and 71 cm depth (Depth C) in mouldboard ploughing (MP) and non-inversion tillage (NIT) systems in conventional (CONV) and organic (ORG) farming. Different crops were present in CONV and ORG during each time window. Cross-correlation functions presented are (a) ambient air temperature versus soil temperature at Depth A, (b) soil temperature at Depth A versus soil temperature at Depth C, and (c) ambient air temperature versus soil temperature at Depth C. Ambient air temperature and soil temperature at Depth A (d) and ambient air temperature and soil temperature at Depth C (e) are also displayed. Correlations within black dashed horizontal lines on cross-correlation plots indicate non-significance.

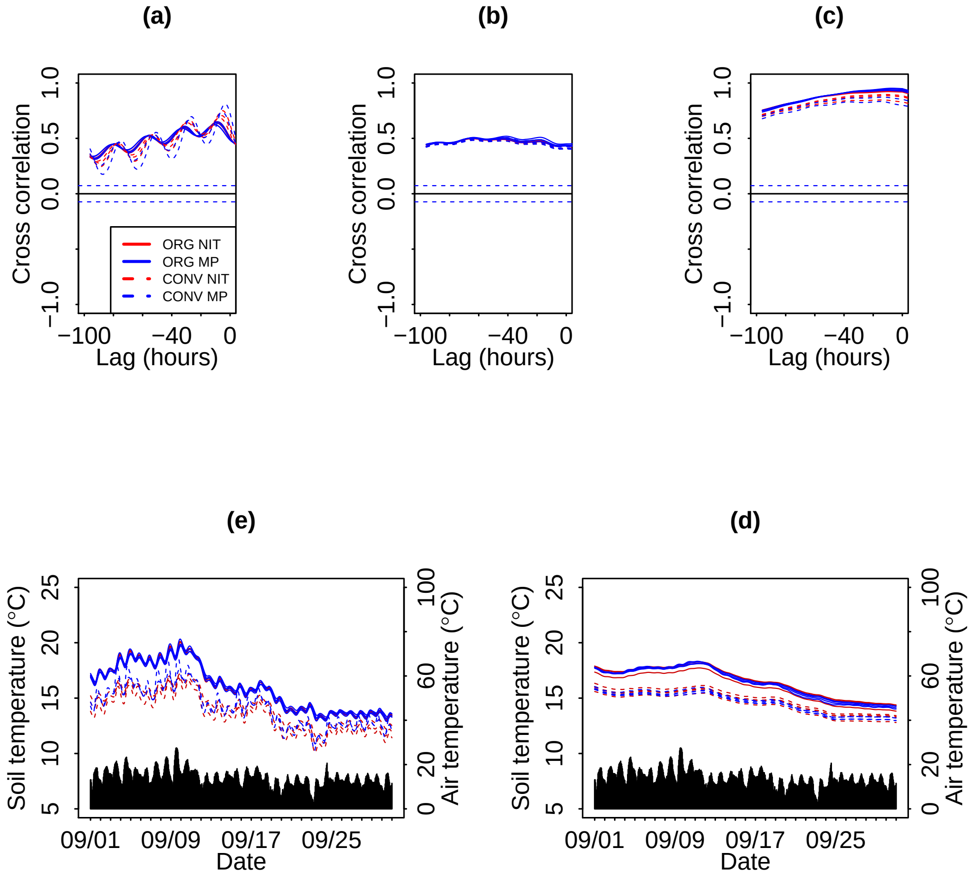


Figure 5.8: Soil temperature and cross-correlation function plots for September 2012 (96 hour lag max). Soil temperature (T) was measured at 11 cm depth (Depth A) and 71 cm depth (Depth C) in mouldboard ploughing (MP) and non-inversion tillage (NIT) systems in conventional (CONV) and organic (ORG) farming. Different crops were present in CONV and ORG during each time window. Cross-correlation functions presented are (a) ambient air temperature versus soil temperature at Depth A, (b) soil temperature at Depth A versus soil temperature at Depth C, and (c) ambient air temperature versus soil temperature at Depth C. Ambient air temperature and soil temperature at Depth A (d) and ambient air temperature and soil temperature at Depth C (e) are also displayed. Correlations within black dashed horizontal lines on cross-correlation plots indicate non-significance.

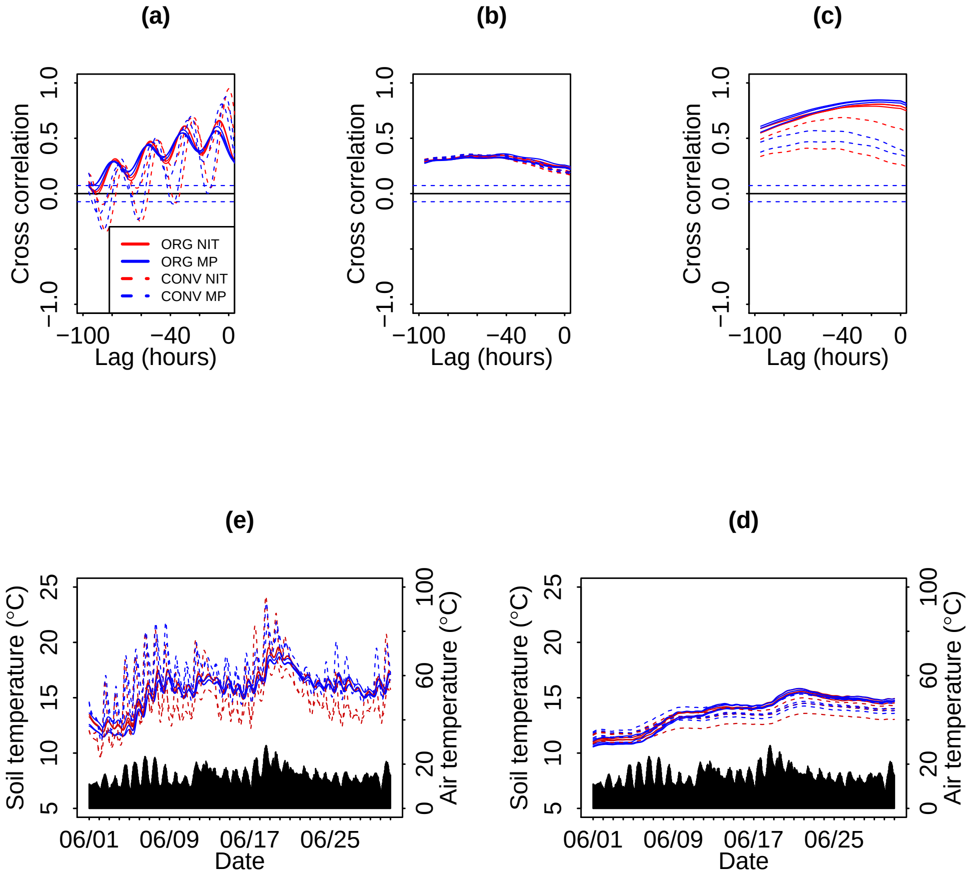


Figure 5.9: Soil temperature and cross-correlation function plots for June 2013 (96 hour lag max). Soil temperature (T) was measured at 11 cm depth (Depth A) and 71 cm depth (Depth C) in mouldboard ploughing (MP) and non-inversion tillage (NIT) systems in conventional (CONV) and organic (ORG) farming. Different crops were present in CONV and ORG during each time window. Cross-correlation functions presented are (a) ambient air temperature versus soil temperature at Depth A, (b) soil temperature at Depth A versus soil temperature at Depth C, and (c) ambient air temperature versus soil temperature at Depth C. Ambient air temperature and soil temperature at Depth A (d) and ambient air temperature and soil temperature at Depth C (e) are also displayed. Correlations within black dashed horizontal lines on cross-correlation plots indicate non-significance.

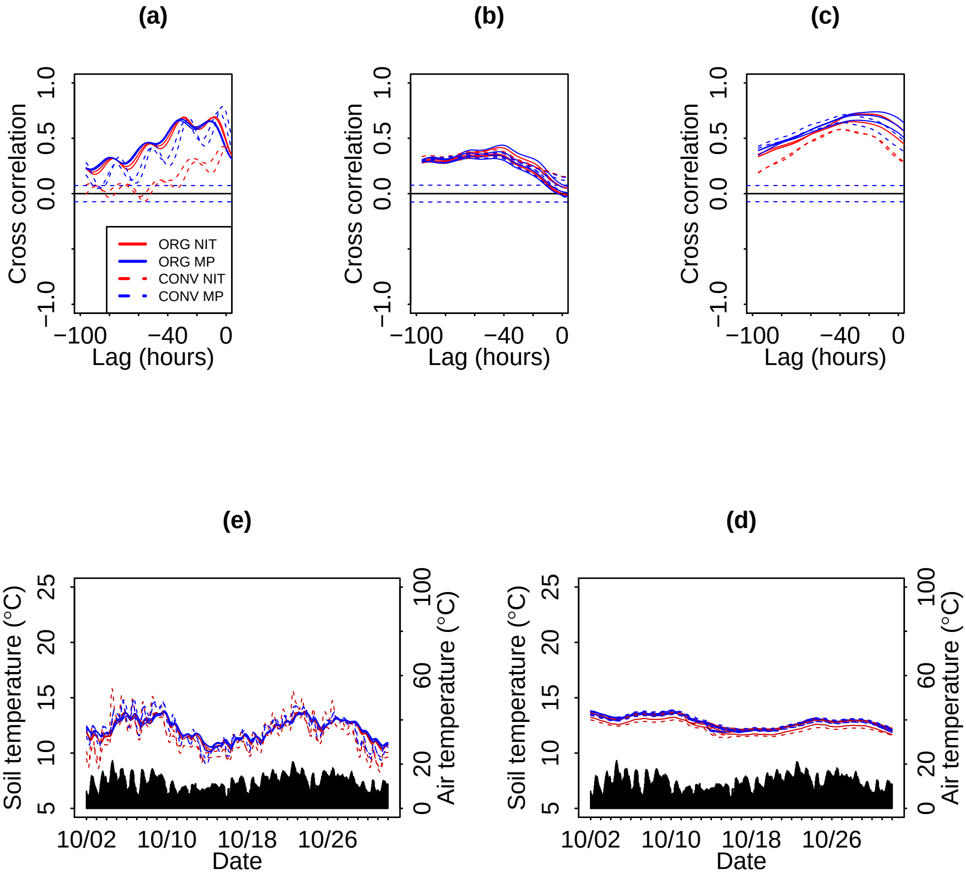


Figure 5.10: Soil temperature and cross-correlation function plots for October 2013 (96 hour lag max). Soil temperature (T) was measured at 11 cm depth (Depth A) and 71 cm depth (Depth C) in mouldboard ploughing (MP) and non-inversion tillage (NIT) systems in conventional (CONV) and organic (ORG) farming. Different crops were present in CONV and ORG during each time window. Cross-correlation functions presented are (a) ambient air temperature versus soil temperature at Depth A, (b) soil temperature at Depth A versus soil temperature at Depth C, and (c) ambient air temperature versus soil temperature at Depth C. Ambient air temperature and soil temperature at Depth A (d) and ambient air temperature and soil temperature at Depth C (e) are also displayed. Correlations within black dashed horizontal lines on cross-correlation plots indicate non-significance.

Table 5.5: Summary table of soil temperatures averaged over time window and sensors[1]

	Depth A								Depth C							
	CONV				ORG				CONV				ORG			
	MP		NIT		MP		NIT		MP		NIT		MP		NIT	
	Soil T	SD	Soil T	SD	Soil T	SD	Soil T	SD	Soil T	SD	Soil T	SD	Soil T	SD	Soil T	SD
June 2012	15.72	1.55	15.53	1.26	15.59	1.05	15.80	1.10	14.34	0.46	14.50	0.44	14.41	0.52	14.54	0.53
September 2012	14.22	1.80	13.89	1.63	16.00	2.09	16.00	2.14	14.58	0.94	14.72	0.94	16.37	1.37	16.34	1.31
June 2013	16.81	2.05	14.86	2.21	15.59	1.70	15.82	1.76	13.46	0.93	13.22	0.90	13.74	1.50	13.79	1.42
October 2013	12.12	1.38	11.70	1.48	12.17	0.90	12.07	1.00	12.84	0.52	12.65	0.52	12.82	0.55	12.68	0.51
Overall average	14.72	1.69	14.14	1.61	14.93	1.49	15.12	1.52	13.80	0.71	13.77	0.70	14.33	0.99	14.34	0.94

[1] Soil temperature (T) was measured at 11 cm depth (Depth A) and 71 cm depth (Depth C) in mouldboard ploughing (MP) and non-inversion tillage (NIT) systems in conventional (CONV) and organic (ORG) farming. Different crops were present in CONV and ORG during each time window. Standard deviation (SD) of the time series is also presented.

Table 5.6: Summary table of maximum lag values from cross-correlation functions comparing air temperature and soil temperature at Depth A and Depth C [1]

	Air T vs Depth A				Depth A vs Depth C				Air T. vs Depth C			
	CONV		ORG		CONV		ORG		CONV		ORG	
	MP	NIT	MP	NIT	MP	NIT	MP	NIT	MP	NIT	MP	NIT
June 2012	-4.00	-5.00	-8.00	-8.67	-16.00	-16.00	-6.33	-7.33	-29.50	-27.75	-22.75	-24.00
September 2012	-4.00	-6.00	-9.75	-8.67	-14.50	-12.67	-7.50	-8.67	-52.75	-64.00	-53.00	-64.00
June 2013	-3.50	-1.00	-8.33	-7.00	-51.50	-52.00	-14.33	-17.00	-60.75	-66.00	-44.50	-46.25
October 2013	-3.50	-1.00	-31.33	-8.50	-37.00	-39.00	-23.00	-27.50	-50.00	-54.25	-48.75	-45.00
Overall average	-3.75	-3.70	-14.00	-8.30	-29.75	-26.80	-12.39	-13.70	-48.25	-53.00	-42.25	-44.92

[1] Cross-correlation functions were used to identify the time lag (delay) that maximised correlation between air temperature and soil temperature (T) at Depth A (11 cm depth), T at Depth A and Depth C (71 cm depth), and air T and soil T at Depth C (Legendre and Legendre, 2012). Negative lag times represent the time (hours) shift between air T (or T at Depth A) and reaction in sensors at Depth A or Depth C. Soil Ts were monitored in mouldboard ploughing (MP) and non-inversion tillage (NIT) in conventional (CONV) and organic (ORG) farming. Different crops were present between CONV and ORG in each time window. Overall averages include all sensors with data from broken sensors and erroneous data omitted. Maximum lag was set at -96 hrs therefore values of -96 hrs should be read as ≤ -96.

TILLAGE SYSTEM EFFECTS ON SOIL TEMPERATURES IN ORGANIC FARMING

In organic farming, ORG NIT (15.12 ± 1.52°C) was warmer than ORG MP (14.93 ± 1.49°C) at Depth A and ORG NIT (14.34 ± 0.94°C) was slightly warmer than ORG MP (14.33 ± 0.99°C), averaged over all time windows and crops (Table 5.5). The lag time where maximum positive correlation occurred in MP was more negative than NIT by 5.7 hrs in the CCF comparing ambient air T to soil T at Depth A, averaged over all time windows and crops. Lag time where maximum positive correlation occurred in MP was less negative than NIT by 1.3 hrs in the CCF comparing soil T at Depth A to soil T at Depth C. MP was also less negative than NIT by 2.7 hrs in lag time where maximum positive correlation occurred in the CCF comparing ambient air T to soil T at Depth C, averaged over all time windows and crops.

FARMING SYSTEM EFFECTS ON SOIL TEMPERATURES

Depth A ORG temperature sensors reacted with smaller amplitude fluctuations than CONV sensors (Figures 5.7, 5.8, 5.9, 5.10). In Sept. 2012 Depth A (and C) all ORG sensors under grass clover showed warmer soil temperatures than CONV sensors under sugar beet for the entirety of the month. In June 2013 Depth (and C) ORG sensors were cooler than CONV sensors, on average, at the beginning of the month but quickly warmed up after around 1 week to become warmer than CONV sensors for the rest of the month (Figures 5.7, 5.8, 5.9, 5.10). Temperature sensors at Depth A and Depth C were positively correlated in all cases across all lag times analysed. CCFs of air temperature versus soil T at Depth A showed larger fluctuations in amplitude in CONV than in ORG. The lag time where maximum positive correlation occurred in CONV was less negative than ORG by 7.8 hrs in CCF comparing ambient air T to soil T at Depth A. ORG was less negative in CCFs comparing soil T at Depth A and Depth C by 15.2 hrs as well as in the CCF comparing ambient air T with soil T at Depth C by 7.2 hrs.

5.4. Discussion

Reactions of soil water content (SWC) and soil temperature (T) were compared between soil under mouldboard ploughing (MP) and non-inversion tillage (NIT) using time-series analysis. These tillage systems were compared over four one-month time windows in 2012 and 2013 in a conventional farming (CONV) and an organic farming (ORG) system. Each farming system contained a distinct crop rotation and organic matter management. Cross-correlation functions (CCFs; Eqs. 5.1 and 5.2) were used to locate the lag time where maximum positive correlation occurred. These peak lag times were usually consistent between sensors within each time window, however there was quite some variation between windows. The lag time where maximum positive correlation occurred is the time needed for SWC and soil T sensors located in topsoil and subsoil to react to either precipitation or ambient air temperature changes, respectively.

5.4.1. Soil water content dynamics between tillage systems

CONV MP at Depth A (0–21 cm depth) tended to react with greater amplitude fluctuations than NIT, agreeing with the findings of McCoy et al. (2006), and the hypothesis of the current study. Time-series analysis using CCFs of precipitation versus soil water content (SWC) sensors in the topsoil (Depth A) and subsoil (Depth D; 80–101 cm depth), as well as topsoil versus subsoil sensors were able to detect differences in reaction speed between tillage systems. However, tillage effects were not consistent throughout all soil depths. There was no tillage effect in CONV in the precipitation versus SWC in topsoil comparison, however MP reacted faster than NIT by 10.6 hrs to precipitation in subsoil, averaged over all time windows and crops. Soil water was therefore able to reach subsoil 10.6 hrs faster in MP than NIT in CONV averaged over all time windows, with biggest differences occurring in the June time windows, and agreeing with the hypothesis that MP would react faster than NIT. Looser soil in CONV MP, with lower soil penetration resistance (Chapter 4 of this thesis), likely aided the movement of water past the plough pan. Similar to the current study, McCoy et al. (2006) found that fluctuations in soil water content were higher in conventional tillage than in no-till, and that amount of soil water storage is higher in no-till than in conventional tillage.

In organic farming SWC in NIT reacted faster than MP to precipitation in both topsoil (1.0 hrs) and subsoil (1.4 hrs), on average, contrary to the hypothesis. Soil structure may have been more conducive to water movement due to grass clover, higher soil organic matter content, soil aggregate stability, and earthworm species present (Chapters 2 and

4 of this thesis). Reduced tillage practises such as NIT in temperate climates, would be expected, through soil structural changes, to increase drainage and water holding capacity over the long term and have lower soil Ts and higher SWC in spring resulting in delayed planting dates (Holland, 2004; Soane et al., 2012).

Because soil density is higher in NIT water is forced to flow through preferential flow channels which create a more heterogeneous flow pattern where the 30 cm long CS616 sensor rods are less likely to detect changes in volumetric water content. CONV and ORG fields may also be expected to differ in terms of soil density due to more organic inputs and mechanical weeding and due to a wider variety of crops with differing root structures (e.g., legumes) in ORG. Soil mixing in MP creates a more homogeneous medium where downward flow between topsoil and subsoil is more uniform spatially, giving greater likelihood that CS616 sensors at Depths A and Depths D in the same plot both react to the same precipitation event. In CONV during the June 2012, June 2013, and October 2013 time windows the majority of CCFs comparing time series of MP from Depth A and Depth D correlate positively, whereas the majority of CCFs of time series from NIT do not agree.

Precipitation events during the Sept. 2012 and June 2013 time windows did not cause a response from soil water content sensors at Depth D within the 96 hr maximum time lag, likely because of low amounts of precipitation (Figures 5.3, 5.4, 5.5, 5.6). Therefore, CCFs of precipitation in Sept. 2012 and June 2013 versus sensors at Depth D indicate essentially no correlation. Whereas CCFs of precipitation in June 2012 and Oct. 2013 versus soil water content sensors at Depth D did show peaks, indicating that sensors were reacting to the greater amount of precipitation in these time windows (Figures 5.3, 5.4, 5.5, 5.6). This resulted in a mix of positive and negative correlations between CCFs of SWC data in topsoil versus subsoil. Water transport to depth is dependant on crop water uptake and soil heterogeneity that produces preferential flow, thus reducing the likelihood that both topsoil and subsoil sensors would react to the same precipitation event (i.e., as seen in the current study) (Beven and Germann, 2013).

5.4.2. SOIL TEMPERATURE DYNAMICS BETWEEN TILLAGE SYSTEMS

The sinusoidal pattern of daily air temperatures resulted in a similarly shaped pattern in CCFs of soil T in topsoil. Largest fluctuations in soil temperatures (T) and resultant CCFs were evident across all time windows and crops at Depth A (11 cm depth). There was no overall difference between tillage systems in terms of reaction times in CONV in the CCF comparing ambient air temperature to soil T in topsoil (or precipitation versus SWC). However, in subsoil MP reacted faster than NIT to fluctuations in ambient air temperature, contrary to expectations, but agreeing with tillage effects on SWCs at the same depth. Heat conduction in soil is highly dependant on the arrangement of the mineral, water, and gas phases. Mineral particles, which conduct heat the best, are connected by water which conducts heat to a lesser degree, and separated by the gas phase which is the worst of the phases at heat conduction (Koorevaar et al., 1983). Parkin et al. (2013) used time-series analysis and found smaller amplitude fluctuations in no-till compared to conventional tillage due to an insulating effect that was caused by a thicker snow cover collected on crop residues, though no great differences were seen in the current study contrary to predictions. Gupta et al. (1984) found minimal differences between mouldboard ploughed and no-till systems on soil temperatures in the U.S.A. because of crop residue cover. It could be expected that systems with higher SWC would have more moderated diurnal soil temperature fluctuations due to the high heat capacity of water (Topp and Ferré, 2002), but that was not observed in the current study.

The behaviour of soil T in organic farming showed that NIT reacted 5.7 hrs faster than MP in topsoil but that in subsoil MP reacted faster than NIT by 2.7 hrs (similar to CONV), averaged over all time windows, partially confirming hypotheses. This difference in behaviour with depth indicates that soil structure and soil physical properties change throughout the profile. Soil density as indicated by soil penetration resistance may play a role in this difference with profile depth. In Chapter 4 it was demonstrated that treatment differences in soil penetration resistance tended to disappear in subsoil.

5.4.3. Soil water content and soil temperature dynamics in conventional and organic farming

In general, SWC sensors in tillage systems in ORG (under potato and grass clover) reacted to precipitation events with smaller amplitude fluctuations in soil water contents and in correlations than tillage systems in CONV (under sugar beet and spring barley followed by a yellow mustard/fetch/facelia mix) as was predicted in the hypothesis. Gunapala and Scow (1998) also found less variation in SWC in organic than conventional farming, but under a Mediterranean climate in Californa (U.S.A.). Soil penetration resistance was lower in ORG than CONV likely from lack of loosening from ploughing and from natural re-consolidation and soil organic matter was higher in organic inputs in ORG not present in CONV (i.e., manures and leguminous crops in the rotation)(Chapters 2 and 4 of this thesis). Higher SOM likely resulted in a higher buffering capacity to changes in soil water content and soil dry bulk density resulted a slower movement of water through the soil matrix (Putte et al., 2012).

In terms of soil temperature, ORG NIT was warmer than MP in both the topsoil and subsoil averaged over all time windows and crops, whereas the opposite was true in CONV where MP was warmer than NIT. Averaged over all time windows and crops, ORG was warmer than CONV likely due to albedo differences from higher soil organic matter in ORG than CONV. CONV reacted faster in topsoil by an average of 7.8 hrs but by subsoil ORG reacted faster by an average of 7.2 hrs. Differences between farming systems including organic inputs and tillage in particular not only effected soil T (and SWC) reactions within topsoil and subsoil but also between topsoil and subsoil.

Finally, it should be noted that in 4 of 6 CCF comparisons the affects of tillage system were the same in SWC and soil T data. Relations between tillage systems were directionally the same for SWC and soil T CCFs in the precipitation/ambient air T versus topsoil sensors, both farming systems of the topsoil versus subsoil sensor, and for CONV in the precipitation/ambient air T versus subsoil.

5.4.4. Merits and challenges facing analysis of continuous data

The current study demonstrated that time-series analysis of continuous data can distinguish differences in SWC and soil T dynamics between tillage systems and between farming systems. The current study builds upon previous work by using time-series analysis on continuous data not only averaging, using multiple sensors in a randomised block design field study at two depths, and by monitoring conventional and organic farming simultaneously (Fabrizzi et al., 2005; Licht and Al-Kaisi, 2005; Parkin et al., 2013; Wu et al., 1997). Observations regarding soil heterogeneity effects on precipitation reaching subsoil and amplitudes of absolute SWC and soil T as well as correlations are examples of added insights gained by using time-series analysis of continuous data at multiple soil depths. Time-series analysis in the current study has allowed for greater insights to be garnered that otherwise may not have been seen with a more conventional analysis of variance assessment. For example, continuous measurements of soil CO_2 efflux using data measured at high repetition frequency allowed for the detection of significant effects because of variation missed by the lower measurement frequency type (Ford et al., 2012). In the current study, differences in reaction times of SWC and soil T between tillage systems and farming systems were in general greater than 1 hr averaged over all time windows and crops present. Such differences in SWC and soil T likely would translate to tillage system and farming system differences in nutrient cycling or greenhouse gas emissions, for example.

Whereas point-in-time measurements have been the standard in the past, technologies allowing for greater data resolution in time are becoming more readily available. Dielectric sensors have been increasing in use and one reason for this is their ability to give high temporal data resolution (Robinson et al., 2002). As costs of sensors capable of providing continuous data decrease the challenge remains of employing appropriate analysis techniques that take advantage of the increased amount and resolution of data. Continuous SWC and soil T measurements could be used to guide the timing of farm operations by allowing for the identification of threshold values of soil physical properties, by giving field validation to predictions of soil workability and trafficability, or for scheduling irrigation (Droogers et al., 1996; Laboski et al., 2001; Schulte et al., 2012). Soil water and soil temperature are real-time expressions of soil physical properties and processes and their analysis should incorporate technological advances that can further articulate subtleties in their characterisation.

5.5. CONCLUSIONS

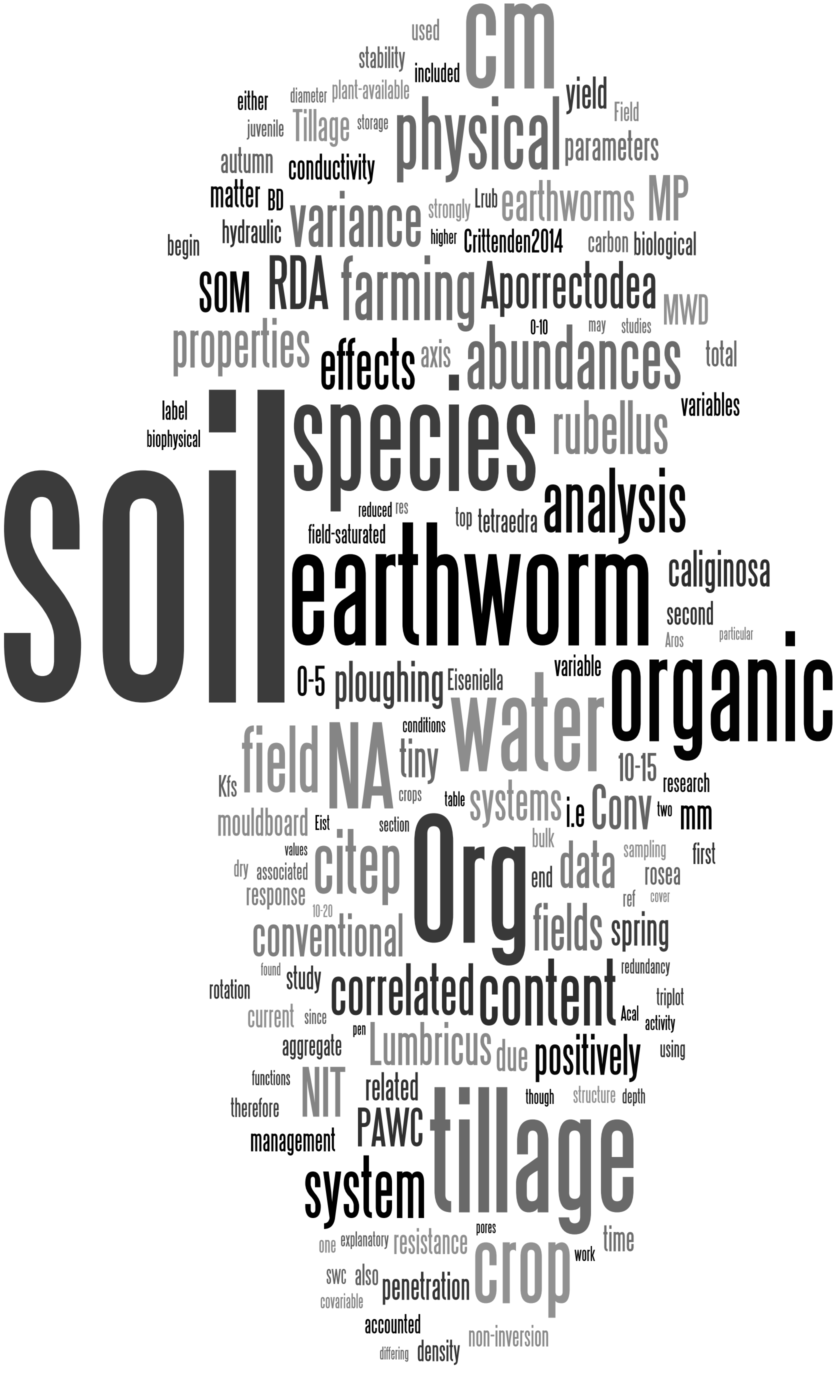
In conventional farming, soil water content reacted faster to precipitation and soil temperature reacted faster to ambient air temperature changes under mouldboard ploughing than under non-inversion tillage in subsoil, whereas there was no tillage effect in topsoil. In organic farming, soil water content reacted faster to precipitation in non-inversion tillage than mouldboard ploughing in both topsoil and subsoil. Soil temperature under non-inversion tillage also reacted faster than mouldboard ploughing in topsoil, however the opposite was true in subsoil where soil under mouldboard ploughing reacted faster than non-inversion tillage, averaged over all time windows and crops. Therefore, tillage-induced differences in soil structure and soil organic matter content manifested in differences in topsoil soil water content and soil temperature dynamics in organic farming but not conventional farming. Spatial heterogeneity of preferential flow patterns displayed themselves in a mixture of positive and negative correlations between topsoil and subsoil sensors.

Comparisons between conventional and organic farming should be made with care since they were separate fields with distinct crop rotations and management practices, though they did contain the same tillage treatments. Given those distinctions, there were clear differences in fluctuations of soil water contents and soil temperatures between conventional and organic farming, regardless of time window or crop compared. Soil temperatures in organic also warmed faster than conventional farming. Soil water contents were less variable in top soils under organic than in conventional farming. Organic farming therefore appears able to resist fluctuations in soil water content and soil temperature better than conventional farming. Overall, conventional farming had faster reactions at the surface soil depth to precipitation and air temperature than organic farming.

Even though tillage system effects on soil water content and soil temperature dynamics were not consistent with depth, in general (4 of 6 time-series comparisons), tillage effects were similar between soil water contents and soil temperatures. This agreement in the behaviour of soil water content and soil temperature indicates a positive correlation between the two.

6

Integrating Soil Physical and Biological Properties in Contrasting Tillage Systems in Organic and Conventional Farming



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Though soil physical and soil biological properties are intrinsically linked in the soil environment they are often studied separately. This work adds value to analyses from Chapters 2 and 4 that evaluated soil biophysical quality of tillage systems under organic and conventional farming systems by correlating physical and biological data otherwise left unexplored. Multivariate redundancy analysis was used to relate data on soil water, soil structure, soil carbon, crop yield, and earthworm species abundances (Aporrectodea caliginosa, Aporrectodea rosea, Eiseniella tetraedra, Lumbricus rubellus). Effects of tillage system (i.e., mouldboard ploughing (MP) and non-inversion tillage (NIT)) on soil physical parameters and on the earthworm species Lumbricus rubellus were similar in organic (fields Org A and Org B) and conventional (field Conv A) farming. Despite differences in measurement times (Org A in autumn 2011 and Org B and Conv A in spring 2012) and crops present at the time of sampling NIT correlated positively with L. rubellus, soil organic matter content, plant-available water content, soil aggregate stability, soil water content, and penetration resistance. Field-saturated hydraulic conductivity was negatively correlated with NIT and was negatively, or not correlated at all, with earthworm species abundances. In the comparison of organic fields, earthworms were positively correlated with the soil's ability to hold water but loosening by ploughing appears to have benefited the conduction of water through soil more than earthworms. More time may be needed for a larger number of earthworm species to colonise soil under NIT that may result in increased field-saturated hydraulic conductivity (e.g., anecic species such as Lumbricus terrestris). Further research could include the investigation of the full gamut of practises within reduced tillage and organic farming systems to identify and maximise their benefit. Effects of cover crops, crop residue management, organic inputs such as green and animal manures and mechanical weeding are amongst factors of interest that drive earthworm community dynamics and related soil structure and function.

6.1. Introduction

To encourage soil physical functioning that improves soil water dynamics, soil structure, and crop yield a reduction in soil tillage intensity by removing ploughing is considered an option (Huwe, 2003; Morris et al., 2010). It is assumed that soil biological activity, largely earthworms, will take up the slack in terms of soil physical functioning (porosity, root penetration, aeration) left by the plough (Huwe, 2003; Tebrügge and Düring, 1999). The majority of studies focused on both soil physical properties/function and reduced tillage often ignore the influence of soil biological activity in field (Mendoza et al. (2011); Chapter 4 of this thesis) or laboratory experiments (Reynolds et al., 2007). The opposite is also true where many studies focused on effects of reduced tillage on soil biology take for granted that earthworms and earthworm species abundances will have beneficial effects on soil water dynamics and soil structure (Chapters 2 and 4 of this thesis).

Earthworms and soil physical properties have been studied simultaneously using various methodologies in-lab and in-field. For example, Ernst et al. (2009) found that *Aporrectodea caliginosa* (endogeic) was positively related to infiltration rate and *Lumbricus rubellus* was positively related to soil water storage in a laboratory study with soil columns containing functionally distinct earthworm species. Earthworm burrows have been isolated in existing field experiments in order to ascertain their contribution to water infiltration (Edwards, 1992; Shipitalo, 1999). van Schaik et al. (2013) found that earthworm distribution in a field study was related to amount and effectiveness of macropores using soil pits dug after rainfall experiments with brilliant blue dye. Under controlled field conditions Fischer et al. (2014) related earthworm density and ecological type, infiltration capacity, plant species diversity, and plant functional group richness using linear mixed-effect models and path analysis at the Jena site in Germany. Plant functional groups affecting earthworm biomass in particular explained spatial and temporal variation in infiltration capacity. Finally, field studies may also simply relate earthworm and soil physical properties after implementing tillage treatments. Capowiez et al. (2009) found that tillage systems did not affect earthworm abundances or water infiltration but did change soil porosity. However an integrated analysis of all parameters was not done. Multivariate analysis applied in a field study by Ernst and Emmerling (2009) showed that reduced intensity tillage systems changed soil organic carbon distributions in topsoil and benefited earthworm species diversity, even though *Aporrectodea caliginosa* correlated positively to ploughing.

There is a deficit of primary field research in which earthworm species abundances are related to soil physical properties, and soil water retention and conductivity in particular, in reduced tillage systems under organic and conventional farming. This chapter attempts to integrate soil biological, here meaning earthworm species abundance data, with soil physical data. Relations amongst earthworm species abundances and soil physical properties are explored between tillage systems (non-inversion tillage and mouldboard ploughing) and in conventional and organic farming.

6.2. Materials and Methods

This chapter is an exploration of soil biological (earthworm species abundances) and soil physical data from two separate studies conducted simultaneously.

6.2.1. Site description

The studies reported in Chapters 2 and 4 of this thesis took place at the PPO Lelystad experimental farm of Applied Plant Research, Wageningen University and Research Centre, in The Netherlands (52° 31'N, 5° 29'E). Soil at the station is a calcareous marine clay loam (23% clay, 12% silt, 66% sand) with a pH of 7.9. Precipitation is 825 mm on average annually and the average annual temperature is 9.7° C (Royal Netherlands Meteorological Institute, 2013).

6.2.2. Experimental design and farming practices

Tillage systems were arranged in randomised complete block designs in two sets of fields managed in parallel under either organic farming or conventional farming (see Fig. 2.1 from Chapter 2). Data from two fields under organic farming and one under conventional farming were used in the current work. Organic and conventional fields were separated by 120 m.

Organically managed fields received annual animal manure applications of 20–40 Mg ha^{-1} yr^{-1}, though no manure was applied to Organic field A in autumn 2011 since the following leguminous crop (wheat/faba) did not require additional nitrogen. Conventional fields received yearly synthetic fertiliser applications and during the growing season were treated bi-weekly with herbicides, whereas organic fields had not received synthetic fertilisers or herbicides since 2002. Organic certification was awarded in 2004. Tillage systems were established in 2008 in all experimental fields and organised in randomised complete block designs. Tillage systems were mouldboard ploughing (MP) to 23–25 cm in autumn and cultivation to 8 cm for seedbed preparation and non-inversion tillage (NIT) with yearly sub-soiling using a Kongskilde Paragrubber to 18–23 cm in autumn and cultivation to 8 cm for seedbed preparation. Tillage treatments within each farming system received equal amounts of fertilisers or animal manures. For plot plans and detailed crop rotation information see Chapters 2 or 4 of this thesis. Crop rotations included mainly root and cereal crops, with the addition of grass and cabbage in organic farming. Cover crops were seeded after main crop harvest when possible.

6.2.3. STATISTICAL ANALYSIS

Multivariate redundancy analysis (RDA) was performed to explore effects of tillage systems on soil physical and biological properties in organic and conventional farming. Data were combined from Chapters 2 and 4 of this thesis and are presented in Table 6.1.

Relations between parameters measured in both Org A in autumn 2011 and Org B in spring 2012, were explored with an RDA with tillage system (non-inversion tillage (NIT) and mouldboard ploughing (MP)) as constraint and field of measurement (Org A and Org B; taken at different times and with different crops) as covariable. Variable 'field' effectively encompasses variance due to all of: timing of sampling (i.e., autumn 2011 or spring 2012), main crop (i.e., spring wheat/faba bean intercrop followed by yellow mustard cover crop or spring wheat followed by winter fetch cover crop), and weather conditions. However, these influences on factor 'field' cannot be disentangled in the current analysis and are therefore examined in the discussion section. Response variables were field-saturated hydraulic conductivity, soil organic matter content, plant-available water content (PAWC), soil aggregate stability, soil water content at the time of sampling, dry bulk density, penetration resistance, soil carbon, crop yield, and earthworm species abundances of *Aporrectodea caliginosa*, *Aporrectodea rosea*, *Eiseniella tetraedra*, and *Lumbricus rubellus*. PAWC is the difference between water contents at field capacity (100 cm suction) and wilting point (15500 cm suction) (Reynolds et al., 2007).

A second RDA was conducted using data from Conv A in spring 2012 (sugar beet main crop) in addition to data used in the first RDA for Org A and Org B. To ensure that values were present a reduced set of response variables was used in the second RDA since samples for soil water retention were not taken in Conv A, and therefore none of soil dry bulk density, PAWC, nor soil carbon stocks could be calculated. Similar to the first RDA, the second RDA used tillage system as constraint and field as covariable.

Several adjustments to the data set had to be made before the RDAs could be performed. Missing values were filled in with parameter averages for that tillage by field combination since the RDA function in the R package 'vegan' (Oksanen et al., 2012) cannot tolerate their absence. Filling in missing values with averages was deemed better than removing the response variable from the analysis so as to maximise the parameters that could be included. Values filled in were two missing PAWC values because of missing values in water retention data in the NIT treatment, and therefore two soil dry bulk densities and the resulting soil carbon were filled in with averages. Furthermore, two NIT and one MP yield sample were missing from Org B and were also filled in with averages. In addition to adjusting for missing values, parameters with multiple depths (i.e., penetration resistance and soil carbon) and pressures (i.e., PAWC) were reduced to one value per plot to match the other parameters and fit into the needed data frame structure in R. Penetration resistance and soil carbon data were summed by depth for each plot to achieve one summarised value per plot. Soil carbon was summed for 0-5 cm and 10-15 cm depths because these were common in both organic fields. PAWCs were calculated using soil water retention curves measured at 0-5 cm and 10-15 cm depths and were calculated per original soil core and then averaged per plot. Finally, to account for differences in crop between fields yield values were standardised following Pettygrove and Plant (2003) where Y_i is the ith yield value, $\bar{Y}$ is average yield for that crop/field combination, and SD is standard deviation of that crop/field combination:

$$Y_s = \frac{Y_i - \bar{Y}}{SD} x100 \tag{6.1}$$

All statistical computations were performed using package 'vegan' (Oksanen et al., 2012) from R (R Core Team, 2012).

6

Interpretation of multivariate plots

Multivariate analysis (MVA) explores and summarises complex data sets that have multiple response variables for every experimental unit (Onofri et al., 2010; Venables and Ripley, 2002). The type of MVA used in the current study, called redundancy analysis (RDA), allows for formal hypothesis testing between data sets (i.e., explanatory and response variables) (Borcard et al., 2011). The effects of tillage system (explanatory variable) on soil biophysical properties (response variables) were of interest in the current study, and variation due to farming system (i.e., organic or conventional) is controlled for (Borcard et al., 2011).

RDA analyses are generally presented in ordination diagrams called 'triplots'. Triplots contain three elements, namely site scores (coordinates of sites in ordination space (i.e., rows in data set)), response variables, and explanatory variables. Diagrams in the current work use symmetric scaling meaning that the triplot can be interpreted using the following rules from Borcard et al. (2011) and which are a compromise between distance and correlation biplot interpretations (personal communications with J. Oksanen and G. Simpson both in January, 2013):

- Projecting an object at right angle on a response or quantitative explanatory variable approximates the position/value of the object along that variable.
- The angles between response and explanatory variables, and between response variables themselves or explanatory variables themselves, reflect their correlations.
- The relationship between the centroid of a qualitative explanatory variable and a response variable (species) is found by projecting the centroid at right angle on the species variable.

- Distances among centroids, and between centroids and individual objects approximate their Euclidean distances.

6.3. RESULTS

In the redundancy analysis (RDA) relating soil physical properties and earthworm species abundances from organic fields both the model and factor 'tillage' were significant ($P < 0.01$). The vertical axis clearly separated tillage systems, that accounted for 16% of total variance (Fig. 6.1). The proportion of variance explained can give some indication as to the importance of that variable or ordination axis, though small proportions can still be significant, as is the case here. Earthworm species *Aporrectodea caliginosa*, *Aporrectodea rosea*, *Eiseniella tetraedra* abundances accounted for 88% of all earthworms in organic fields (Table 6.1) and were not strongly correlated to either tillage system. *Lumbricus rubellus* was 12% of all earthworms in organic fields and was positively correlated with soil organic matter content (SOM) in the top 10 cm, soil carbon (0-5 cm and 10-15 cm), plant-available water content (PAWC) at 0-5 cm, and soil dry bulk density (BD) at 10-15 cm depth. Non-inversion tillage was strongly associated with aggregate stability (MWD) at 0-10 cm and 10-20 cm depths, SOM at 0-10 cm and 10-20 cm depths, soil carbon at 0-5 cm and 10-15 cm, BD at 10-15 cm depth, and PAWC at 0-5 cm. A strong association in the triplot indicates a strong positive correlation and that treatments affected those parameters similarly. All earthworm species abundances were positively correlated with PAWC. Earthworm species abundances were negatively correlated, or not correlated, with field-saturated hydraulic conductivity (K_{fs}). K_{fs} and soil dry bulk density (BD) at 0-5 cm depth were the only parameters closely associated to mouldboard ploughing (MP) in the RDA relating soil physical properties and earthworm species abundances from organic fields.

In the redundancy analysis relating soil physical properties and earthworm species abundances from both organic and conventional fields both the model and factor 'tillage' were significant ($P < 0.01$; Fig. 6.2). Tillage system accounted for 15% of total variance. Tillage system, regardless whether in organic or conventional farming, are separated by the vertical axis. *A. caliginosa*, *A. rosea*, *E. tetraedra* accounted for 90% of all earthworms in Org A, Org B, and Conv A, and were not strongly positively correlated with either tillage system. NIT was positively correlated with *L. rubellus* (10% of earthworms), SOM, MWD, SWC, and penetration resistance. Again, K_{fs} was the only parameter closely associated with MP.

Factor 'field' accounts for a large fraction of variance in both the case where only data from organic fields are included (38% of total variance) and the case where limited parameters are included from organic and conventionally managed fields (46% of total variance). Within factor 'field' effects of organic versus conventional farming, crop, cropping history, and sampling time cannot be disentangled conclusively, and therefore 'field' was included as a conditional variable.

6.4. DISCUSSION

The lower intensity tillage system, non-inversion tillage (NIT) where soil was sub-soiled at a shallower depth than the mouldboard plough (MP) system, favoured most soil phys-

Table 6.1: Input soil physical and earthworm species data used in redundancy analyses.[1]

Field	Tillage	Block	Kfs (cm min^{-1})	SOM 0-10 (g kg^{-1})	SOM 10-20 (g kg^{-1})	PAWC 0-5 (cm^3 cm^3)	PAWC 10-15 (cm^3 cm^{-3})	MWD 0-10 (mm)	MWD 10-20 (mm)	SWC (g kg^{-1})	BD 0-5 (g cm^{-3})	BD 10-15 (g cm^{-3})	pen res (MPa)	C Stock (Mg ha^{-1})	Yield (Mg ha^{-1})	Acal (m^{-2})	Aros (m^{-2})	Eist (m^{-2})	Lrub (m^{-2})	Ljuv (m^{-2})
Org A	MP	1	4.0	35.9	29.2	0.20	0.21	0.65	0.49	221	1.38	1.39	152	69	-46	617	42	392	92	0
		2	4.3	38.4	33.8	0.18	0.19	0.64	0.51	213	1.32	1.48	118	64	-98	667	33	175	25	0
		3	2.4	40.3	33.4	0.15	0.18	0.64	0.46	214	1.47	1.43	139	71	-86	500	25	75	25	0
		4	1.1	46.5	33.3	0.17	0.17	0.64	0.54	223	1.51	1.39	128	67	-125	492	25	175	50	0
	NIT	1	1.0	34.0	34.8	0.19	0.17	0.70	0.60	221	1.43	1.50	165	66	137	325	0	225	8	0
		2	1.6	43.5	34.0	0.19	0.19	0.70	1.12	223	1.43	1.47	134	67	94	242	0	192	117	0
		3	1.3	36.8	34.5	0.16	0.19	0.60	0.95	246	1.34	1.50	154	67	57	325	17	100	33	0
		4	2.5	35.6	33.8	0.18	0.17	0.58	0.72	252	1.42	1.40	161	71	67	283	33	242	83	0
Org B	MP	1	7.6	34.9	31.7	0.18	0.21	0.53	0.54	186	1.26	1.44	110	19	-145	583	8	8	33	0
		2	7.8	34.4	34.1	0.21	0.20	0.59	0.64	188	1.37	1.42	123	19	3	667	8	42	125	0
		3	9.3	34.9	34.8	0.18	0.21	0.63	0.58	195	1.36	1.43	120	20	-5	533	0	17	125	8
		4	8.5	36.6	36.3	0.22	0.22	0.51	0.49	191	1.36	1.38	115	21	-49	325	17	17	75	0
	NIT	1	5.23	40.0	36.4	0.23	0.21	0.54	0.64	185	1.29	1.59	133	23	193	917	8	42	75	0
		2	4.6	40.3	35.1	0.23	0.21	0.44	0.61	181	1.29	1.59	122	23	30	1117	17	117	225	0
		3	6.5	41.2	35.2	0.22	0.20	0.75	0.84	189	1.28	1.64	130	22	-75	567	8	8	117	0
		4	5.1	43.0	37.1	0.24	0.23	0.79	0.93	189	1.30	1.54	139	23	49	825	8	0	283	0
Conv A	MP	1	0.1	29.2	30.5	NA	NA	0.42	0.49	168	NA	NA	114	NA	96	100	8	0	0	0
		2	0.1	28.4	29.6	NA	NA	0.31	0.41	175	NA	NA	119	NA	41	225	0	0	0	0
		3	0.4	27.8	29.1	NA	NA	0.56	0.45	170	NA	NA	121	NA	-38	42	0	0	8	0
		4	0.4	28.5	29.2	NA	NA	0.41	0.42	178	NA	NA	111	NA	-114	233	0	0	0	0
	NIT	1	0.0	32.4	30.3	NA	NA	0.45	0.57	181	NA	NA	152	NA	58	142	8	0	8	0
		2	0.1	32.6	31.6	NA	NA	0.61	0.77	177	NA	NA	154	NA	10	125	8	0	8	0
		3	0.1	34.0	32.2	NA	NA	0.90	0.80	176	NA	NA	173	NA	115	200	0	0	42	0
		4	0.1	30.3	29.8	NA	NA	0.65	0.69	178	NA	NA	171	NA	168	250	25	0	17	0

[1] Measurements were taken in fields that were organically managed (Org A and Org B) or conventionally managed (Conv A) under either mouldboard ploughing (MP) or non-inversion tillage (NIT). Parameters represented are field-saturated hydraulic conductivity (Kfs), soil organic matter content in top 10 cm (SOM 0-10) and second 10 cm (SOM 10-20), soil aggregate stability mean-weight diameter in top 10 cm (MWD 0-10) and second 10 cm (MWD 10-20), soil water content (SWC), soil penetration resistance (pen res), standardised crop yield (Yield), plant-available water content at 0-5 cm (PAWC 0-5) and 10-15 cm (PAWC 10-15), soil dry bulk density at 0-5 cm (BD 0-5) and 10-15 cm (BD 10-15), soil organic carbon content (C Stock), and earthworm species: *Aporrectodea caliginosa* (Acal), *Aporrectodea rosea* (Aros), *Eiseniella tetraedra* (Eist), *Lumbricus rubellus* (Lrub), *Lumbricus* juvenile (Ljuv; juvenile individuals identifiable only to genus level, one individual here).

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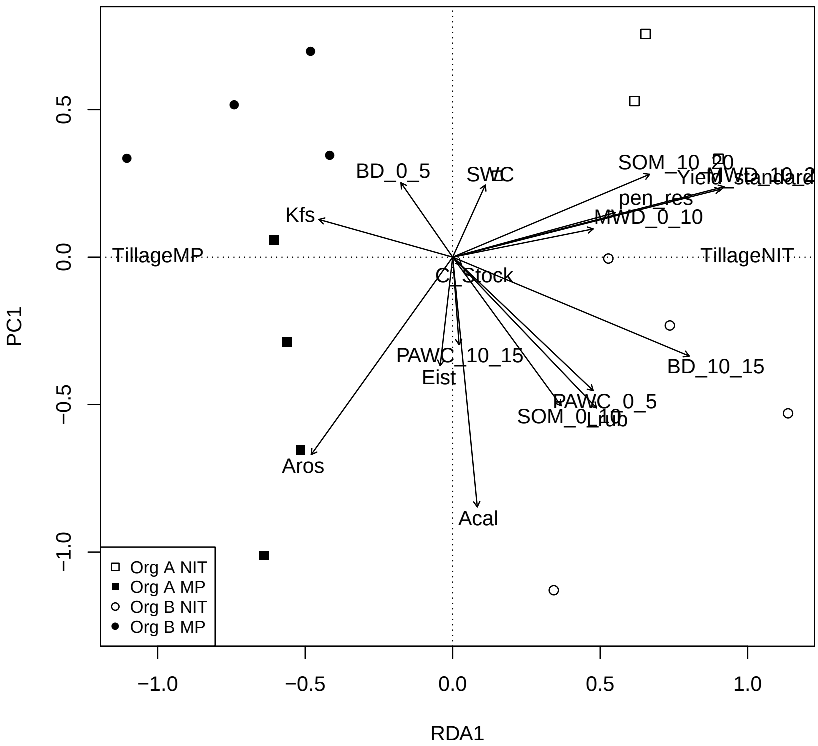

Figure 6.1: Redundancy analysis triplot of soil physical properties and earthworm species abundances from autumn 2011 in Org A and spring 2012 in Org B ($P < 0.01$) constrained by soil tillage system (mouldboard ploughing (MP) or non-inversion tillage (NIT)), $P < 0.01$, 16% of total variance) with Field (Org A, Org B) included as covariable. The first RDA axis explains 22% of variance and the first PCA axis 21% after variance due to field was removed (field accounted for 32% of total variance). Parameters represented are field-saturated hydraulic conductivity (Kfs), soil organic matter content in top 10 cm (SOM_0_10) and second 10 cm (SOM_10_20), soil aggregate stability mean-weight diameter in top 10 cm (MWD_0_10) and second 10 cm (MWD_10_20), soil water content (SWC) at the time of sampling, soil penetration resistance (pen_res), crop yield (Yield_standardised), plant-available water content at 0-5 cm (PAWC_0_5) and 10-15 cm (PAWC_10_15), soil dry bulk density at 0-5 cm (BD_0_5) and 10-15 cm (BD_10_15), soil organic carbon stock (summed 0-5 cm and 10-15 cm; C_Stock), and earthworm species: *Aporrectodea caliginosa* (Acal), *Aporrectodea rosea* (Aros), *Eiseniella tetraedra* (Eist), and *Lumbricus rubellus* (Lrub). One *Lumbricus* juvenile individual identifiable only to genus level was omitted from analysis. Symbols represent site scores.

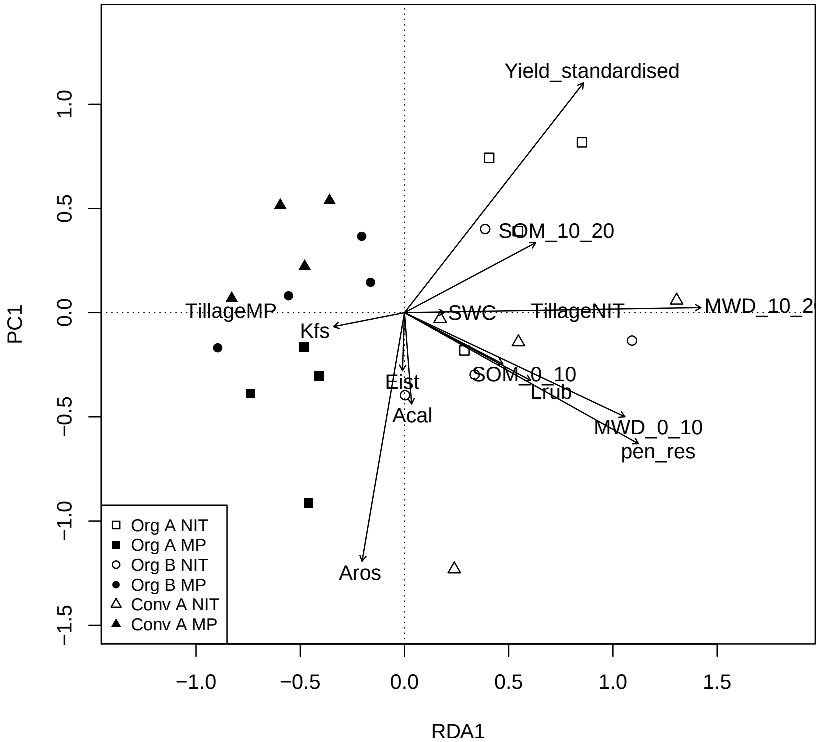

Figure 6.2: Redundancy analysis triplot of soil physical properties and earthworm species abundances from autumn 2011 in Org A and spring 2012 in Org B and Conv A ($P < 0.01$) constrained by soil tillage system (mouldboard ploughing (MP) or non-inversion tillage (NIT), $P < 0.01$, 15% of total variance) with Field (Org A, Org B, Conv A) included as covariable. The first RDA axis explains 25% of variance and the first PCA axis 20% after variance due to field was removed (field accounted for 50% of total variance). Parameters represented are field-saturated hydraulic conductivity (Kfs), soil organic matter content in top 10 cm (SOM_0_10) and second 10 cm (SOM_10_20), soil aggregate stability mean-weight diameter in top 10 cm (MWD_0_10) and second 10 cm (MWD_10_20), soil water content (SWC) at the time of sampling, soil penetration resistance (pen_res), crop yield (Yield_standardised), and earthworm species: *Aporrectodea caliginosa* (Acal), *Aporrectodea rosea* (Aros), *Eiseniella tetraedra* (Eist), and *Lumbricus rubellus* (Lrub). One *Lumbricus* juvenile individual identifiable only to genus level was omitted from analysis. Symbols represent site scores.

ical properties. In particular, plant-available water content (PAWC), representing soil's ability to retain water, in organic farming at 0-5 cm depth was higher in NIT than MP, possibly due to higher soil organic matter content (SOM) in NIT. PAWC at both 0-5 cm and 10-15 cm depths was associated with earthworm species abundances (i.e., *Aporrectodea caliginosa*, *Aporrectodea rosea*, *Eiseniella tetraedra*, and *Lumbricus rubellus*).

It should be noted that earthworm ecological groups consist of a continuum of behaviours as presented by Bouché (1977) and earthworm species do not necessarily follow one rigid categorisation. *L. rubellus*, for example, is generally cited as an epigeic species (Nuutinen, 1992; Curry and Schmidt, 2007; Chapters 2 and 3 of this thesis), though Bouché (1977) situated it between the epigeic and anecic ecological groups. It has also been suggested that *L. rubellus* may behave as an epi-endogeic earthworm (Felton et al., 2009). Tillage effects on earthworms depends on the population structure in terms of relative amounts of juveniles and adults, since juveniles may be more sensitive to physical damage (Bertrand et al., 2015). Stressed soil ecosystems may display a disproportionate amount of juveniles if many individuals are not allowed to reach maturity due to soil disturbance (Klok and De Roos, 1996; Klok et al., 1997). Wyss and Glasstetter (1992) suggested that ploughing would predominantly affect anecic earthworms because of their larger body size and that their permanent burrows would be destroyed. Tillage system effects on soil properties and functions would therefore be expected to differ between tillage systems based on the differential influence on adult and juvenile individuals. To better describe the influence of tillage on earthworms multi-year studies are required (Bertrand et al., 2015). Little, if any, research though has been done to distinguish the influence of earthworm community age structure on soil functions as far as the author is aware.

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Ernst et al. (2009) postulated that the burrowing activity of endogeic and anecic earthworm species aerates and therefore dries soil, yet the shallow yet complex burrow system of the epigeic *L. rubellus* was positively correlated with soil water storage. Conversely, it would be expected that earthworm species abundances would be positively correlated with field-saturated hydraulic conductivity (K_{fs})(Edwards, 1992; Shipitalo, 1999). However the current study shows little or slightly negative correlation. This was due to differences in tillage effects on earthworm species abundances, *A. caliginosa* in particular, between Org A and Org B due to main crop, crop residue management, or timing of sampling effects (Chapter 2 of this thesis). The lack of positive association of earthworm species abundances and K_{fs} suggests that soil macroporosity was dictated more by direct physical effects of ploughing and associated management practices than earthworm burrowing activity. Another factor may have been anecic species known for improving infiltration were not present in any field in the current study. A shift in earthworm species community would shift the pore-size distribution in soil. Soil porosity and hence hydraulic conductivity are, in theory, influenced by earthworm burrowing activity since earthworm borrows are generally 2.5-11 mm in diameter which would be considered to function as water transmission pores (macropore flow) (Greenland, 1979; Syers and Springett, 1983). Average *L. rubellus* burrow diameter is 30 mm and *A. caliginosa* is 25 mm (Springett, 1983). Soil water holding capacity on the other hand is presumed to be influenced by earthworm casts which have pores in the range of 0.003-0.06 mm (Syers and Springett, 1983) and would thus store water (Greenland, 1979). Schmidt and Curry

(2001) noted the importance of soil water condition in affecting earthworm species composition with time.

Tillage system effects on soil physical parameters and *L. rubellus* were consistent between organic and conventional fields. NIT was positively correlated with the earthworm species *L. rubellus*, soil organic matter content, soil aggregate stability, soil water content, penetration resistance, and crop yield in both RDAs despite differing measurement times (Org A in autumn 2011 and Org B and Conv A in spring 2012) and therefore crop present. Earthworms are generally considered to promote soil aggregation (Bardgett et al., 2001). In Chapter 2 of this thesis it was demonstrated that *L. rubellus* consistently benefited from NIT in Conv A over the 4-year study and that *L. rubellus* abundance was strongly positively correlated with soil organic matter content, as was also found in the further analysis done here.

6.5. Conclusions

Tillage effects on biophysical parameters were consistent between farming systems. Non-inversion tillage was associated with higher plant-available water in surface soil of organic farming, higher soil aggregate stability, higher soil organic matter, higher soil carbon, and higher *Lumbricus rubellus* abundance. Field-saturated hydraulic conductivity was the only soil physical parameter higher in mouldboard ploughing due to lower soil density indicated by lower penetration resistance and dry bulk density at 10-15 cm depth. Differing effects of tillage on endogeic earthworms between fields under organic farming were due to different crops present at the time of measurement, point in the crop rotation, residue management, and/or time of measurement.

Soil pore systems and functions were related to earthworms and earthworm species diversity, all of which are influenced by tillage and farming system. However few studies simultaneously investigate these biophysical properties under field conditions. The challenge for future work will be to evaluate both physical and biological soil properties simultaneously in long-term field trials of contrasting tillage systems in conventional and organic farming.

General Discussion

Effects of non-inversion tillage and mouldboard ploughing on earthworm species abundances, soil organic matter, soil structural properties, soil functions, and soil water and soil temperature dynamics were evident in the studies presented in the current thesis.

Non-inversion tillage in conventional farming in both Chapters 2 and 3 consistently increased the abundance of the epigeic earthworm *Lumbricus rubellus*, because of increased organic material left at soil surface and lessened disturbance of the soil. Contrary to our findings, in neither of the arable cropping systems studied by Nuutinen and Pitka (1998) in Finland nor Ernst and Emmerling (2009) in Germany were epigeic species, including *L. rubellus*, found to be higher in the respective reduced tillage systems. The endogeic species *Aporrectodea caliginosa* was consistently higher in mouldboard ploughed soil in one organic field but the opposite was true in the other organic field investigated in this thesis. This was likely due to interactions between soil tillage, crop, cropping history, and organic matter management differences between the fields. Incorporation of organic matter by ploughing may promote endogeic species by increasing food availability (Chan, 2001; Ernst and Emmerling, 2009; van Capelle et al., 2012). Another management strategy employed in Dutch arable landscapes is the field margin strip (Chapter 3). Earthworm species were more abundant, and species richness was higher, in field margin strips than in adjacent arable soil but key species like the anecic *Lumbricus terrestris* was effectively absent from arable fields. Smith et al. (2008) and Roarty and Schmidt (2013) found similar effects of field margin strips after 3 years on earthworm species abundances and also found no evidence of any spill-over effect into adjacent arable soil under conventional or minimum tillage.

Non-inversion tillage improved many soil physical quality parameters as expected (Chapter 4). Non-inversion tillage had higher soil aggregate stability in both conventional and organic farming, higher soil organic matter content, and had higher soil carbon in one organic field but had no effect in the other. Crop yields were also higher in one case under organic farming. However, contrary to the expectation, field-saturated hydraulic conductivity was lower in non-inversion tillage likely because of a lack of continuous macropores due to higher soil density and lack of anecic earthworm species. Hill et al. (1985) also found higher water retention in soil in reduced tillage under corn in Iowa, U.S.A. D'Haene et al. (2008) also concluded that reduced tillage improved soil physical quality, in Belgium under crop rotations that included root crops, as in the current thesis. Though they found reduced tillage improved field-saturated hydraulic conductivity, contrary to the findings presented in this thesis.

Non-inversion tillage was positively correlated with *L. rubellus*, soil organic matter content, plant-available water content, soil aggregate stability, soil water content, and penetration resistance. Earthworm species abundances were positively correlated with soil water holding capacity but negatively correlated with field-saturated hydraulic conductivity in organic farming. The lack of correlation of non-inversion tillage with field-saturated hydraulic conductivity is perhaps due to a lack of anecic species present, likely because soil tillage practises for root crops are too intensive. In a German study, the greater number and continuity of earthworm channels, attributed to *L. terrestris* (anecic) was higher in untilled plots compared to tilled plots (Ehlers, 1975). Earthworm burrows in soil under reduced tillage are more effective flow paths than those in tilled soil (Shipitalo et al., 1994). Ernst and Emmerling (2009) also showed little correlation between soil carbon and *A. caliginosa*, however in Chapter 6 soil carbon was positively correlated with *L. rubellus* contrary to what Ernst and Emmerling (2009) found.

Non-inversion tillage in topsoil of conventional farming, in general, reacted with smaller amplitude fluctuations and reacted slower to fluctuations in precipitation and ambient air temperature than mouldboard ploughing (Chapter 5). These findings agree with those of a Canadian study by McCoy et al. (2006). However, Gupta et al. (1984) found only small differences between mouldboard ploughed and no-till systems on soil temperatures in the U.S.A. because of crop residue cover.

In all chapters of the current thesis, despite variation in crops and weather through time, consistent effects of tillage systems and farming systems have been seen. Large amounts of variance in statistical analyses attributable to field of measurement (organic fields A or B in Chapters 2, 4, 5, 6, conventional fields A in Chapters 2, 4, 5, 6 or B in Chapter 2, and farms in Hoeksche Waard in Ch. 3) were observed even with relatively homogeneous soil, yet consistent tillage effects on soil biophysical quality and soil water and soil temperature dynamics were observed. This consistency of effect affirms the veracity of the results presented in this thesis and implies that they would be expected to be observed elsewhere, at least under similar climatic and agricultural conditions. Factors such as cropping history (i.e., point in crop rotation), crop residue management, and organic input management (i.e., green and animal manures) played more important roles than inherent spatial heterogeneity.

Further research should therefore strive to clarify the roles of management practices in addition to tillage on soil biophysical quality. The roles of cover crops, types and quantities of animal manures, and superficial cultivations including mechanical weeding practises could be investigated in terms of their influences on soil biophysical quality and functions in tillage systems within organic and conventional farming. Crop yield in particular should always be monitored as farmers are the managers of these agroecosystems and crop yield is an important indicator of the feasibility of new soil management practice. More mechanistic understanding of field-scale relations of reduced tillage systems in conventional and organic farming would better inform farm management decisions. Given this better understanding, results could be extrapolated and up-scaled to field and landscape levels using models. Being able to predict change in soil carbon, water holding capacity, and infiltration at field and landscape scales from adoption of reduced tillage in conventional or organic farming would be a significant stride forward and would not only inform land managers but allow for policy relevant communication.

Synchronising rotations in organic and conventional farming, as much as possible since organic is a 6 and conventional is a 4 year rotation in the case of PPO Lelystad, would have allowed more direct comparisons between the farming systems. This leads to the idea that field experiments, even in replicated designs, need to be monitored over long periods of time, certainly a time period that encompasses an entire crop rotation in order to encapsulate influences from that rotation and range of management practices therein.

Efforts have been made throughout this thesis to use the most appropriate statistical methods. Mixed effects models are becoming, if they are not already, the standard. Even when analysis of variance model assumptions broke down in the Hoeksche Waard earthworm study (Chapter 3) we employed the rarely used, but seemingly most appropriate generalised linear mixed-effects models with repeated measures. Time-series analysis was used in Chapter 5 with the idea that it better suited the exploration of large amounts of automatically collected continuous soil water content and soil temperature data. Whereas point-in-time measures or averaged continuous data might have been used in the past, time-series analysis allowed for insights into speed of reactions of tillage systems in contrasting farming types. A further application of the soil water content and soil temperature data could be to validate model output from SWAP (Van Dam, 2000). SWAP is a model that "simulates transport of water, solutes and heat in the vadose zone". Soil water content and soil temperature are effectively real-time expressions of agglomerated soil physical processes and functions, and modelling could be used to upscale the dynamics of these properties to better assess the impacts of soil management decisions on the provision of ecosystem services.

In recent decades there has been an increasing recognition among researchers of the links between soil biological activity and soil structure and function, however a need for improved collaboration between soil ecologists and soil physicists remains (Bottinelli et al., 2015).

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SUMMARY

Soil ecosystem functions are relevant to arable farming. For example, soil functions like the ability to hold and transmit water are important for plant growth and the timing of farm operations. Soil functions are based on soil organic matter content, soil structure, and the actions of earthworms. Since earthworm species act on soil structure in varying ways, resultant soil functions vary as well. Reduced tillage may be implemented to improve soil physical and biological quality (i.e., functioning) in both conventional and organic farming systems. In this thesis I investigated effects of reduced tillage in conventional and organic farming systems on soil physical and biological quality and soil water and temperature dynamics. Earthworms were also studied in arable field margin strips.

In Chapter 2 I quantified the effects of non-inversion tillage (a reduced tillage system that loosens subsoil at 30 – 35 *cm* depth) and mouldboard ploughing on earthworm populations in conventional and organic farming. Earthworm species abundances were monitored over short (up to 53 days) and medium term (up to 4 years) in tillage systems at the PPO Lelystad research farm of Wageningen University and Research Centre. Mouldboard ploughing decreased earthworm abundances one and three weeks after ploughing, suggesting that direct (e.g., physical damage) and indirect (e.g., relocation of food resources) mechanisms were at work. Earthworm populations had recovered by the following spring. *Aporrectodea caliginosa* (endogeic) dominated the earthworm community (76%) and anecic species were <1% of all earthworms in all tillage and farming systems over the entire study. In conventional farming, reduced tillage increased *Lumbricus rubellus* (epigeic), but did not affect total earthworm abundance. In organic farming, on the other hand, mean total earthworm abundance was 297 m^{-2} in reduced tillage and 430 m^{-2} in mouldboard ploughing, across all sampling dates over the medium-term study. Earthworm species abundances were positively correlated with soil water content and soil organic matter which are generally acknowledged to be beneficial to earthworms. In conclusion, reduced tillage in conventional farming affected earthworms differently than in organic farming, which may be accounted for by interactions between soil tillage, crop, and organic matter management.

In Chapter 3 earthworm species assemblages were monitored on 4 farms in Hoeksche Waard, The Netherlands, from 2010 to 2012. I expected that arable field margin strips (grassy strips bordering arable fields) and non-inversion tillage would contain higher earthworm species abundances including epigeic and anecic species in particular and have higher soil organic matter and soil water content than adjacent mouldboard ploughing. *Aporrectodea rosea*, *Lumbricus rubellus*, *Lumbricus terrestris*, and *Lumbricus castaneus* were significantly more abundant in field margin strips than adjacent mouldboard ploughed soil. Contrary to what I expected there was no decreasing trend in abundances with distance from field margin strips into adjacent arable soil, probably because disturbance and relocation of food resources from ploughing were too great. A comparison of earthworms in mouldboard ploughed soil versus in soil under non-inversion tillage was conducted on the same farms where field margin strips were sampled. *Lumbricus rubellus*, *Aporrectodea rosea*, and *Lumbricus terrestris* were significantly more abundant overall in non-inversion tillage than mouldboard ploughed soil. An important finding of this study is that despite variation in environmental conditions and soil properties between samplings, farms, and crops, both field margin strips and non-inversion tillage could be observed to positively affect earthworm species richness. Earthworm species richness was likely higher in field margin strips and non-inversion tillage because of more topsoil organic matter and less physical disturbance of the soil. *Lumbricus terrestris*, a species known to promote water infiltration, remained low in arable fields even though they were present in adjacent areas.

In Chapter 4 I compared non-inversion tillage to the standard mouldboard ploughing practice in terms of soil physical functions, soil structural parameters, soil organic matter, and crop yield in conventional and organic farming again at the PPO Lelystad research station. Mouldboard ploughing is used to control weeds, loosen soil, incorporate organic material, and prepare a seedbed. However, ploughing destroys soil structure, reduces soil organic matter, and compacts subsoil if driven upon. The non-inversion tillage system investigated here is an attempt to alleviate these negative impacts of ploughing, and is a reduced tillage system adapted to Dutch crop rotations that include root crops, and may also incur lower operational costs from less labour. Non-inversion tillage improved soil water retention in one organic field but had no effect in another. Non-inversion tillage increased soil aggregate stability in both conventional and organic farming, increased soil penetration resistance, increased soil organic matter content, and had higher soil carbon in one organic field but had no effect in the other. Crop yields were higher in non-inversion tillage in one organic field with spring wheat/faba bean and incurred no yield penalty neither in the second organic field nor in the conventional field. Field-saturated hydraulic conductivity, an indicator of the topsoil's ability to infiltrate and transmit water, was lower in non-inversion tillage. Because non-inversion tillage improved or did not negatively affect most soil physical quality parameters it could viably be recommended to farmers.

Reactions of soil water content to precipitation and soil temperature to ambient air temperature changes between non-inversion tillage and mouldboard ploughing in conventional and organic farming were explored in Chapter 5. Non-inversion tillage may change soil water and soil temperature regimes due to modifications in soil structure, soil cover, and soil organic matter content. Soil water content was collected at 0–21 cm and 80–101 cm depths and soil temperature was collected at 11 cm and 71 cm depths. These data were analysed using time-series analysis in four one-month time windows in 2012 and 2013 with hourly time steps. Soil water contents at 0–21 cm in conventional farming reacted with similar speeds between tillage systems, but soil water content sensors in mouldboard ploughing reacted 11 hrs faster than non-inversion tillage at 80–101 cm, on average. Soil water contents under organic farming reacted faster to precipitation in non-inversion tillage than mouldboard ploughing by 3.5 hrs at 0–21 cm and 1.4 hrs at 80–

101 cm, averaged over all four time windows and crops present during those windows. Soil temperature sensors had similar reaction times between tillage systems at the 11 cm depth, but mouldboard ploughing was 4.8 hrs faster averaged over all time windows at the 71 cm depth. In organic farming, there was no tillage effect on monthly average soil temperature at either depth. Soil temperature sensors reacted 5.7 hrs faster in non-inversion tillage at 11 cm and 2.7 hrs slower in non-inversion tillage at 71 cm depth. Soil water content and soil temperature in conventional farming reacted with greater amplitude to precipitation and ambient air temperature fluctuations than in organic farming at 0–21 cm, in all time windows. Tillage effects and differences between conventional and organic farming could be discerned using time-series analysis of continuous soil water content and soil temperature data. Effects were not always consistent between topsoil and subsoil depths, suggesting that tillage and farming systems' influence on soil water content and soil temperature changed with depth.

In the last of the main chapters, Chapter 6, a need to integrate data from Chapters 2 and 4 was addressed. Data from these chapters were collected from the same tillage treatments and farming systems at the PPO Lelystad research farm. I used multivariate redundancy analysis to relate soil water, soil structure, soil carbon, crop yield, and earthworm species abundances (*Aporrectodea caliginosa*, *Aporrectodea rosea*, *Eiseniella tetraedra*, *Lumbricus rubellus*) in non-inversion tillage and mouldboard ploughing in both conventionally and organically farmed fields. Even with measurement time differences between fields used and crops present at time of sampling, non-inversion tillage correlated positively with *L. rubellus*, soil organic matter content, plant-available water content, soil aggregate stability, soil water content, and penetration resistance. The one parameter that was consistently reduced by non-inversion tillage was field-saturated hydraulic conductivity, which was negatively or only slightly correlated with earthworm species abundances. Organic fields showed positive correlation between earthworms and soil water holding capacity.

Non-inversion tillage had consistent effects on soil physical and biological quality, in general, despite variation between sampling times, sampling locations, and crops present. Non-inversion tillage increased soil water storage, soil organic matter, and soil structural parameters, and had a consistently positive influence on the epigeic earthworm species *L. rubellus*.

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This book is dedicated to Dafne and Eva. I didn't know I could love half as much.

To the rest of you, I tip my cap in thanks. You know who you are. We've driven together, dug together, drank coffee together. I know it has been said before, but it bares repeating again, thank you. It is my belief that we should acknowledge and appreciate those who aid us whether it be in large or small contribution. That is why I've done it so many times before, I've said thank you to you all, but I'm saying it again now. Thank you.

To my supervisory team Lijbert Brussaard, Mirjam Pulleman, Marius Heinen, and Jan van den Akker, you stuck with me through thick and thin, thick meaning my skull of course. Patience and wisdom are virtues. My family Los Crittendens y Scotneys, The Urquias and Edreiras. Robertsons and Hamiltons. You have my everlasting heartfelt and hardy thanks. My collaborators Ron de Goede, Esperanza Huerta, and Bert Vermeulen. To those I "supervised", thanks. Marta Manrubia Freixa, Natasja Poot, Tamilarasi Eswaramurthy, Peter and Tony, Sil, Kirsten, Natalie, Bas, Marianne Hoogmoed, Steffan, and Anais. Plus any number of young people from PPO Lelystad. Colleagues and friends Sultan Mahmood, Joop Kroes, Paul Torfs, Pieter Hazenberg, Gerben Bakker, Harm Gooren, Eduard Hummelink, Tamás Salanki, I truly truly could not have managed to finish without your help and guidance. Farmers who kindly allowed us on their land. Joke and Leen de Geus (best soup in the land), Cees Schelling, Henk Scheele, Marcel Tramper, and Joost van Strein. My officemates Helton Nonato de Souza, Edvaldo Sagrilo, Joana Frazão, and Walter Andriuzzi. Thanks to all of the other Ph.D. and M.Sc. students in SOQ. PPO Lelystaders Derk van Balen, Wiepie Haagsma, Wijnand Sukkel, Wout, Peter van Dijk, Wim van den Berg, and thanks to the lunch ladies for the free cookies. Caroline, Marnella, Esther, and Anita especially of administrative staff in the Atlas building are very kind and helpful. Jaap Nelemans, Gerlinde, and Willeke were always helpful and interesting to talk with. More abroadly speaking, my experience with SUSTAIN was a wonderful learning experience. I learned so much taking a project from the realisation at the poster session in Jalapa, Mexico that we shared research interests, to writing, then implementing an international research project. Thanks Guénola.

Along the path one might call a career I've encountered a number of kind souls along the way. After getting a summer job with the Ministry of Agriculture because I was enthusiastic, I met Jim, Cory, and Gnaph one summer afternoon in a corn field over a Brookston clay. Their cuban cigars intrigued me enough to approach them, and they introduced me to Bev Kay who employed me for the following two years at the University of Guelph. And who coincidentally gave me the contact information that led me to work in Brittany (vive la Bretagne). To this day I still tie plastic bags the way I was taught by Ranee in Bev's lab. Working at UofG I met John Lauzon, but it was only after I carried a backpack full of biosolid waste to class that I caught his attention. He thought I was 'keen' and contracted me to do an M.Sc., later he discovered that, in his words, I was just dirty. John employed me again later and let me live above his garage. Gary, Dave, and Peter were also characters in this story who taught me an exceptional amount. You never know where life will lead us.

To our 'Dutch' friends. You've been our family in The Netherlands. Quite literally you've been our life line. You know why. Some of you we knew before we arrived in The Netherlands, Marjolein, Arjan, Lars, Sheila, and Charlie. Some we met later Roland and Carolina, Milja and Vlado, Simon and Ana, and Hanneke and Nils. You've given us the life part of having lived in The Netherlands.

Un abrazo muy fuerte para todos nuestros amigos en Madrid. Viva el barrio del Berro! Quentin, Alex, Verity, Ines, Javi, Maria, Theo, Anna, Marcus, Nepheli, Chiara, Vasilius. Pidame un tinto de verano ya.

And to all of those I've left out, don't worry, you're only forgotten momentarily.

A

Curriculum Vitæ

Experience

- July 2015 - July 2017, Postdoctoral Associate, Cornell University, United States of America
  Updating New York State whole-farm nutrient mass balances and phosphorus index with Nutrient Management Spear Program (<http://nmsp.cals.cornell.edu/>)

- Nov. 2013 - Dec. 2015, Guest Researcher, Wageningen University, The Netherlands
  Scientific journal article and PhD thesis writing are the main tasks. Participation in SUSTAIN project meetings.

- Aug. 2009 – Oct. 2013, Ph.D. Candidate, Wageningen University, The Netherlands
  Thesis covers soil quality in reduced tillage systems in conventional and organic farming. International collaborations were initiated, students were successfully supervised, and multiple field campaigns were organized simultaneously.

- Mar. 2008 – Sep. 2008, Research and Development Coordinator, Western Ag Innovations, Canada
  Soil nutrient bioavailability. Created and sustained a strong network in the scientific community, supported collaborative research projects with new and existing clients and developed potential markets. Presented two scientific posters international conferences and published several technical documents.

- Aug. 2007 – Feb. 2008, Assistant Engineer, Cemagref(IRSTEA), France
  Assessed agri-food and dairy industry effluents for phosphorus recycling potentional in Brittany through bibliographical searches and industry surveys. Used GIS to identify high emission areas and assess viability of co-treatment between agrifood sectors. Results were summarized at a stakeholders meeting and as a written report.

- May 2006 – Dec. 2006, Research Associate, University of Guelph, Canada
  Project and team management included organization and construction of a field research project to investigate environmental impacts of agricultural management. The office component consisted of analysis and writing of scientific journal publications on manure management and bacteria transport, and nitrogen transport and modeling.

- Sep. 2005 - Mar. 2006, Research Assistant, Global Forum on Agricultural Research, Italy
  GFAR is a stakeholder-led initiative that fosters cost effective collaborative partnerships among stakeholders involved in agricultural research for development. I updated and further developed GFAR's Civil Society Organizations' database, edited and proof read the Newsletter, and assisted and participated in workshops and meetings. A literature review on agricultural research partnerships was undertaken as a part of an external review of GFAR's partnership program. The results of which were presented at an international workshop in Rome in January 2006.

- Sep. 2002 - Sep. 2005, M.Sc. Candidate, University of Guelph, Canada
  Focus was on transport of nutrients and bacteria through soil. Tasks included design, construction, and implementation of soil water collection and monitoring system.

- Jan. 2003 - Apr. 2004, Teaching Assistant, University of Guelph, Canada
  Two advanced level courses (Groundwater 3060 and Soil Management 4090) were assisted upon. Conducted weekly seminars, graded assignments and exams, and provided student consultations.

- Sep. 2000 - Aug. 2002, Student Assistant, University of Guelph, Canada
  Part-time lab duties were soil and corn analysis. Summer full-time duties included soil and plant sampling, and assisting on various research projects.

- May 2000 - Sep. 2000, Summer Assistant, Ontario Ministry of Agriculture, Food, and Rural Affairs, Canada
  Field work included soil sampling, collecting physiological data on corn plants, and GPS mapping.

EDUCATION

- 2009 - present, Ph.D. Soil Quality, Wageningen University, The Netherlands
  Soil water and earthworm dynamics in reduced tillage of organic and conventional farming.

- 2002 - 2005, M.Sc. Soil Science, University of Guelph, Canada
  Effect of Manure Management Practise on *E. coli*, Nitrogen, and Phosphorous Loss in Agricultural Water.

- 1998 - 2002, B.Sc. (Honours) Environmental Science, University of Guelph, Canada Earth and Atmosphere Science Major. Area of emphasis in Environmental Impact Assessment.

Conferences and Presentations

- Biological and physical soil quality of reduced tillage in conventional and organic farming in The Netherlands
  Presented by S.J. Crittenden, at COST Short-term Scientific Mission, 12-16 May, 2014, Madrid, Spain.

- Integrated soil quality of reduced tillage systems
  Presented poster by S.J. Crittenden and M.M. Pulleman, Wageningen UR, The Netherlands at the First International Conference on Global Food Security, 29th September - 2nd October, 2013. Noordwijkerhout, The Netherlands.

- Effect of tillage on earthworms over short- and medium-term in conventional and organic farming
  Oral presentation at SUSTAIN update meeting, 25-27 Feb. 2013, Kasteel Hoekelum, The Netherlands.

- Can reduced disturbance improve soil physical quality through earthworms?
  Presented poster at FAO/IAEA International Symposium on Managing Soils for Food Security and Climate Change Adaptation and Mitigation, 23 – 27 July 2012, Vienna, Austria; EUROSOIL 2012, 2-6 July 2012, Bari, Italy.

- SUSTAIN project, a SNOWMAN network collaboration
  Oral presentation at ELN-FAB European Seminar: Applying functional agrobiodiversity in the Mediterranean 14 - 15 June 2012, Avignon, France.

- Effect of Reduced Soil Disturbance on Soil Physical Quality and Earthworm Density
  Presented poster at Soil Science in a Changing World, 18-22 September 2011, Wageningen, the Netherlands.

- Can reduced tillage and field margins improve soil water dynamics through stimulation of earthworms?
  Presented poster at The 9th International Symposium on Earthworm Ecology 5-10th September 2010, Xalapa, Mexico

COLLABORATIONS AND WORKSHOPS

- COST Short-term Scientific Mission
  Influence of cover crops on soil properties in vineyards and olive groves, 12-16 May 2014, Madrid, Spain.

- SUSTAIN: Soil Functional Biodiversity and Ecosystem Services, a Transdisciplinary Approach
  <http://www.snowmannetwork.com/main.asp?id=110>

- ECOfinders: Ecological Function and Biodiversity Indicators in European Soils
  <http://ecofinders.dmu.dk/>

- BASIS: Reduced tillage for sustainable arable agriculture
  <http://www.biokennis.org/nl/biokennis-3.htm>, <http://www.biokennis.org/nl/biokennis-3/showdossier/Niet-kerende-grondbewerking-in-akkerbouw-e htm>

- Biopore workshop: Ecohydrological modelling- Linking earthworms and preferential flow
  <http://brandenburg.geoecology.uni-potsdam.de/users/schroeder/biopore/workshop.html>

PUBLICATIONS

- Biophysical soil quality of reduced tillage in conventional and organic farming
  S.J. Crittenden, Ph.D. thesis. 2015 (this thesis).

- Effect of tillage on earthworms over short- and medium-term in conventional and organic farming
  Crittenden, S. J., Eswaramurthy, T., de Goede, R. G., Brussaard, L., and Pulleman, M. M. Applied Soil Ecology, 2014, 83, 140–148.

- Earthworm assemblages in field margin strips and reduced tillage: an on-farm study
  S.J. Crittenden, E. Huerta, R.G.M. de Goede, M.M. Pulleman. European Journal of Soil Biology, 2015, 66, 49-56.

- Soil physical quality of reduced tillage systems in conventional and organic farming
  S.J. Crittenden, N. Poot, M. Heinen, M.M. Pulleman. Soil and Tillage Research, 2015, 154, 136-44.

- Soil water and temperature dynamics under reduced tillage in conventional and organic farming
  S.J. Crittenden, N. Poot, M. Heinen, D. van Balen, M.M. Pulleman. Soil and Tillage Research (submitted)

- Integrating biophysical evaluation of reduced tillage systems
  S.J. Crittenden

- Effect of manure management practices on *E. coli*, phosphorus, and nitrogen loss in agricultural water
  Crittenden, S.J. 2005. M.Sc. thesis, University of Guelph, Guelph, Ontario, Canada

B

Education Statement

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)
- Biophysical soil quality of tillage systems in conventional and organic farming

Post-graduate courses (5.6 ECTS)
- Geostatistics; PE&RC (2010)
- Soil ecology; PE&RC (2010)
- Multivariate statistics; PE&RC (2010)
- Introduction to R for statistical analysis; PE&RC (2011)

Laboratory training and working visits (1.5 ECTS)
- Effect of cover crops on soils properties in vineyards and olive groves (COST STSM); Universidad Autónoma de Madrid (2014)

Invited review of (unpublished) journal manuscript (0.9 ECTS)
- Pedobiologia: earthworm functional attributes (2010)
- Plant and Soil: earthworms, stabilization of SOM in aggregates (2012)

Competence strengthening / skills courses (3.3 ECTS)
- PhD Competence assessment; WGS (2009)
- Teaching and supervising thesis students; DO (2010)
- Techniques for writing and presenting a scientific paper; WGS (2011)
- Career assessment; WGS (2013)
- PDCI (Post-doc career development initiative) post-doc retreat (2013)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.5 ECTS)
- PE&RC Weekend (2009)
- PE&RC Day (2009)
- Soil biology retreat; organization of PhD input (2011)

Discussion groups / local seminars / other scientific meetings (7.5 ECTS)
- Climate change & soil-water-atmosphere interactions (2009-2013)
- BASIS project meetings; PPO Lelystad research farm group meetings (2009-2013)
- Young environmental sciences group meetings (2010-2013)
- Global soil fertility: the role of next generation smart fertilizers (2011)
- Soil functional biodiversity and ecosystem services, a transdisciplinary approach (SUSTAIN project) meetings (2011-2013)
- Ecological functions and biodiversity indicators in European soils (EcoFINDERS) meetings (2011-2013)

International symposia, workshops and conferences (9 ECTS)
- 9th International symposium on earthworm ecology (2010)
- Netherlands annual ecology meeting (2010, 2011)
- Wageningen soil conference: soil science in a changing world (2011)
- Eurosoil international congress (2012)
- International conference on managing soils for food security and climate change adaptation and mitigation (2012)
- European learning network on functional AgroBiodiversity (2012)

Lecturing / supervision of practical's / tutorials (0.3 ECTS)
- Conservation agriculture (2010)

Supervision of 2 MSc students
- Effect of non-inversion tillage on soil structure and water flow regulation in temperature climates
- Effect of conventional and non-inversion tillage systems on earthworm dynamics and diversity under organic and conventional systems

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