UNIVERSITY OF GLOUCESTERSHIRE

ASSESSING THE IMPACT OF NO-TILL ON WATER RELATED SOIL FUNCTIONS AND THE ROLE OF FARMER NETWORKS IN KNOWLEDGE EXCHANGE AND IMPLEMENTATION

A thesis submitted to the University of Gloucestershire in accordance with the requirements of the degree of PhD in the School of Natural and Social Sciences

By

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Abstract

No-tillage is a non-inversion farming practice that is becoming more widely used in farming and often considered to enhance soil functions, by increasing soil organic matter levels and thereby improving soil structure. Knowledge about the effects of different management practices on separate soil functions is important to understand potential trade-offs between them. Studies have shown that no-tillage affects soil functions of water purification and water retention and can reduce erosion rates and inputs from agriculture to water bodies, however evidence from north western European countries is still limited. Alongside this gap in evidence about the physical impacts of no-tillage, knowledge about how farmers share knowledge about no-tillage, a knowledge intensive practice, and the role of farmer networks is still growing.

This paper presents results from interdisciplinary (PhD) research which measured the effect of no-tillage on water related soil functions in a UK case study and analysed the distribution of no-tillage knowledge through farmer networks. The field-scale monitoring compares two neighbouring farms (one using conventional ploughing and the other no-tillage) with similar soil and topographic characteristics to assess spatial and temporal changes in soil and water variables. The 2-year monitoring included nutrient analysis of surface and sub-surface soil samples, bulk density, soil moisture, infiltration capacity, surface runoff and analysis of Dissolved Reactive Phosphorous (DRP), Total Phosphorous (TP) and Suspended Solids (SS) in downstream waters. Farmers' networks were mapped using Social Network Analysis (SNA) to reveal the nature and extent of their knowledge exchange about no-tillage. This was complemented by semi-structured interviews with farmers to understand their reasons for implementing no-tillage. This paper presents findings from both aspects of this research. The soil and water data show varying impacts of no-tillage on soil functions and water quality with different soil types and climate. The no-tillage fields had higher bulk density and soil organic matter content and thereby increasing the soil moisture levels, but the free-draining porous limestone was providing greater benefits under no-tillage in this study compared with the lime-rich loamy soil with high silt and clay content.

The SNA suggests that farmers' networks expanded with the conversion to no-tillage and that their main influencers were other more experienced no-tillage farmers. In this respect I question the role of external organisations in supporting no-tillage adoption. The research offers a significant new contribution to the field as it assesses the effects of no-tillage on water purification and retention functions of the soil, and at the same time contributes to understanding the dynamics of farmer networks and the link to implementation.

Keywords: Field scale monitoring, soil functions, no-tillage, SNA, farmer interviews

Author's declaration

I declare that the work in this thesis was carried out in accordance with the regulations of the University of Gloucestershire and is original except where indicated by specific reference in the text. No part of the thesis has been submitted as part of any other academic award. The thesis has not been presented to any other education institution in the United Kingdom or overseas.

Any views expressed in the thesis are those of the author and in no way represent those of the University.

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List of abbreviations

AES	Agri-environment Schemes
AIS	Agricultural Information Systems
C	Carbon
CAP	Common Agriculture Policy
CoGaP	Codes of Good Agricultural Practice
CoPs	Communities of Practice
CT	Conventional tillage
CT-C	Conventional farming practices on lime-rich loamy soil
CT-S	Conventional farming practices on Cotswold Brash
Defra	Department for Environment, Food and Rural Affairs
Dim1	First dimension
Dim2	Second dimension
DOP	Dissolved organic Phosphorous
DRP	Dissolved reactive phosphate
DSS	Decision Support System
DWPA	Diffuse water pollution from agriculture
EAFRD	European Agricultural Fund for Rural Development
EAGF	European Agricultural Guarantee Fund
ESS	Ecosystem services
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FF	Followers:following ratio
FID	Farmer innovation diffusion
FLM	Functional Land Management
GAEC	Good Agricultural and Environment Condition of land
ICT	Information and communication technology
ITPS	The Intergovernmental Technical Panel on Soils
KCl	Potassium chloride
LEAF	Linking Environment and Farming

N	Nitrogen
NH_3	Ammonia
$NH4^+$	Ammonium
NO_2	Nitrite
NO_3^-	Nitrate
NoPs	Networks of Practice
NT	No-tillage
NT-C	No-tillage farming practices on lime-rich loamy soil
NT-S	No-tillage farming practices on Cotswold Brash
NVZs	Nitrate Vulnerable Zones
P	Phosphorous
PCA	Principle component analysis
PO_4^{3-}	Phosphate
PP	Particulate Phosphorous
RDP	Rural Development Programme
RT	Reduced tillage
SES	Socio-ecological system
SMR	Statutory Management Requirements
SNA	Social network analysis
SOC	Soil organic carbon
SOM	Soil organic matter
SSKNs	Socio-spatial knowledge networks
SSM	Sustainable Soil Management
TP	Total phosphorous
UK	United Kingdom
WFD	Water Framework Directive

1 Introduction

The problem of soil degradation is as old as settled agriculture, but the extent and impact of this degradation on both human welfare and the environment is ever increasing (Lal and Stewart, 2012), and significant reductions in soil quality have been documented in the United Kingdom (UK), as well as the rest of the world (Montgomery, 2007, Ray et al., 2012, Ray et al., 2013). Globally, an estimated 24% of the inhabited land area is affected by human-induced soil degradation, with Europe being slightly higher at 26% (Oldeman, 2012). Socio-economic pressures which accelerate intensive land use are important drivers of this trend. Deforestation, cultivation of marginal lands, intensive farming, chemical usage, overgrazing, population growth, transmigration and infrastructure development in ecologically sensitive areas have all been identified as important causes of the global increase in soil degradation (Lal and Stewart, 2012).

Soil degradation reduces the soil's capacity to provide important ecosystem services and functions. Ecosystem services (ESS) is a concept that was developed to quantify the multifunctionality of ecosystems (Hassan et al., 2005). It describes the services that ecosystems provide to humankind, such as provisioning services (e.g. biomass and food provision), regulating services (e.g. water purification and flood mitigation), supporting services (e.g. soil formation and nutrient cycling) and cultural services (e.g. recreation and aesthetic value) (Millenium Ecosystem Assessment (Program), 2005, Schulte et al., 2014). The concept of ESS includes the quantification of services from agricultural ecosystems that are, when explicitly focusing on the soil-based ESS, commonly referred to as soil functions (Baveye et al., 2016, Schulte et al., 2014, Dominati et al., 2010).

A number of soil functions that good quality soils deliver have been identified (Schulte et al., 2014, Schulte et al., 2015), for example: i) production of food, fibre and (bio)fuel; ii) water purification; iii) carbon (C) sequestration; iv) habitat for biodiversity; and v) recycling of nutrients and agro-chemicals (Schulte et al. 2014). Together these can quantify the importance of soils for ecosystems and the environment in addition to food provisioning. Soils must be managed sustainably to maintain good soil quality so that this important resource can continue to deliver private and public goods in the long-term (Smith et al., 2016).

However, evidence shows that the management of agricultural soils is currently unsustainable. The ten most significant soil threats to agricultural land causing soil degradation from a global perspective have been identified as: soil erosion, loss of soil organic carbon (SOC), nutrient imbalance, soil acidification, soil contamination, waterlogging, soil compaction, soil sealing, salinization, and loss of biodiversity (FAO and ITPS, 2015a). These threats are largely accelerated by intensive agricultural management impeding the soils' capacity to deliver important functions to ecosystems and the humanity.

Intensive agricultural management is characterized by intensive tillage systems, often referred to as conventional tillage (CT) (Townsend et al., 2015), in combination with excessive removal of crop residues and unbalanced use of chemical fertilizers. Together these contribute to degradation, for example, by aggregating soil losses by soil erosion due to the lack of soil protection under such management, but also as a result of reductions in the SOC levels that are crucial for good soil quality (Lal, 2015).

In addition to the impact that this intensive management has on the soil resource and long-term farm sustainability, depleting the soil's capacity to function also has a high economic price tag for society. Graves et al. (2015) explored the cost of soil degradation in England and Wales and estimated that the annual cost in the two countries was between £0.9 and £1.2 billion, dependent on the type of degradation, soil type, land use and ESS. Loss of soil organic matter (SOM) was associated with the highest cost (47%), followed by soil compaction (39%) and erosion (12%), but 80% of the total costs occur off-site and a large proportion is related to impact on environmental water quality, drinking water quality, flood mitigation and greenhouse gas regulation. Similarly, Oldeman (2012) reported that the most important type of degradation is caused by water erosion, affecting 56% of the degraded area globally and 52% of the total area affected by human-induced soil degradation in Europe.

The severity of these processes, with both on-site (soil loss by water erosion) and off-site effects of both water contamination (Oldeman, 2012, Graves et al., 2015) and flooding (Graves et al., 2015), calls for more knowledge about the water purification and retention functions of the soil and their responses to different farm practices. These are the functions provided by soil that allow storage of water in soil pores, water infiltration, transmission as deep percolation, and water filtering and purification by the interaction with soil particles and biota through the soil matrix (FAO and ITPS, 2015a). The effect of different soil degradation processes on the separate soil functions is often overlapping due to the complex interactions between variables, for example a change in the physical variable of soil structure will have direct or indirect consequences for all functions. The extent of the effects will, however, differ between the functions, but more research is needed about the interactions between these.

No-tillage (NT) is a low intensity farming system that entails no soil inversion and is often combined with cover crops, crop rotations and crop residue (this system is often referred to as Conservation Agriculture and is outlined in more detail in Section 2.3) in order to conserve soils (soil conservation is here defined as the reversal of soil degradation through appropriate land use and management practices (FAO, 2020)) and soil water by improving soil health and structure (Lahmar, 2010). Research has shown that NT farming can have a positive effect on a range of soil parameters, such as SOM content, aggregate stability and water holding capacity (Kassam et al., 2014, Hobbs et al., 2008), but the effects are variable because of the importance of site-specificity and consideration of different local climatic conditions and soil properties for successful implementation (Virto et al., 2014). Therefore, results from studies assessing NT systems in Europe often lack consensus (discussed in further detail in Chapter 4). Much of the research has been conducted in the USA and applicability of NT in the UK and the rest of Europe is less well documented (Soane et al., 2012), and specifically understanding of how NT impacts water purification and water retention functions of the soil and their responses to different farm practices is limited.

To tackle challenges regarding intensive production, soil degradation and threats to soil functions, there is a need for farmers who are currently not managing their soils sustainably to adapt their practices (Baird et al., 2016). Such changes in farming practice can be brought about in different ways, this can be through providing an enabling environment for farmers who are willing to adopt, or through regulations or stimulating voluntary change of practice with incentives using, for example, agri-environmental policies, and by educating and informing farmers with knowledge, advice and awareness raising. The latter has traditionally been the role of the agricultural advisory services, but is increasingly taking place in peer-to-peer farmer networks as ‘formal’ advisory systems have become fragmented (Ingram and Mills, 2019). Whilst a number of soil improving or best management practices are increasing implemented in the UK (Alskaf et al., 2019), there is still a relatively low uptake of NT, potentially due to uncertainties regarding how to successfully carry out the practice on different soil types and under different weather conditions, and the demand for a high level of experiential knowledge

(Soane et al., 2012, Townsend et al., 2015, Alskaf et al., 2019). Farmers tend to rely on each other's experience when the advisory services are limited or not "fit for purpose" to sustain innovative farming systems such as NT (Ingram and Mills, 2019).

The social networks of farmers are therefore important for both farmer learning and decision-making (Rogers and Kincaid, 1981), and farmers often view their peers as their main source of advice (Wood et al., 2014). Scholars have assessed the role of social ties in the adoption of sustainable farming practices and found that they are important in enhancing knowledge exchange (Oerlemans and Assouline, 2004, Cadger et al., 2016, Isaac, 2012). Knowledge intensive farming systems, such as NT, often require situated and experiential knowledge (Leeuwis and Van den Ban, 2004), resulting in farmers taking on the role of 'innovators' and sharing their own experiences of farming practices in their social networks (Knowler and Bradshaw, 2007, Ingram, 2010, Schneider et al., 2012, Bellotti and Rochecouste, 2014). These interpersonal networks are known to be important, but their role in NT implementation is still uncertain and under-researched.

1.1 Research aims and objectives

There have been numerous studies investigating the effect of different farming practices on soil and water quality. However, these studies rarely consider separate soil functions or the trade-offs between them, nor do they look at the social dynamics of the networks that are affecting farmers' decisions about the implementation of such practices. This research will aim to address this.

The overall aim is to contribute to knowledge about the effect of NT on soil and water and to provide an in-depth understanding of the role of social networks of NT famers in the transition from CT to NT farming. To achieve this the thesis will: firstly, develop and undertake an appropriate methodology to understand the effects of different crop and soil management practices (which contribute to NT) on soil functions in a case study area in the UK. Secondly, it will investigate the nature of information flow and knowledge exchange between NT farmers, and the dynamics of farmers' social networks. Four research objectives were formulated:

1. To review recent and relevant literature to create an overview of the current knowledge on the effects of NT practices on soil functions in Europe, with a particular focus on the water-related soil functions of water purification and regulation. This will investigate contradictions and coherence within the literature and assess which NT practices represent the greatest controversies and assess potential trade-offs between soil functions under different climatic conditions.

2. To establish a monitoring programme for this study for collection, analysis and interpretation of soil and water data to assess effects of NT practices on water related soil functions.

3. To assess the applicability of NT as a sustainable system in the UK and its potential to enhance soil properties and specifically the soil functions of water purification and retention by evaluating the overall effects of shifting from CT to NT systems.

4. To analyse NT farmers' engagement with social networks, specifically in relation to the nature of information flow, knowledge exchange and learning between farmers, and to identify the potential of farmer networks to enable this knowledge exchange.

1.2 Thesis structure

The thesis comprises ten chapters. **Chapter 1** provides the rationale for the study based on the problem of soil degradation resulting from intensive agricultural practices impeding soil functions. Alternatives to CT farming practices that can enhance soil functions, and the different ways that change of practice can be brought about are discussed, and the potential of NT identified. The chapter concludes with a section outlining the aims and objectives for the study.

Chapter 2 provides the context for the research and expands on the concepts introduced in Chapter 1, describing the different types of degradation that are threatening the functionality of agricultural soils, with specific focus on the water purification and retention functions. Soil and water policies in the European Union (EU) and the UK are presented and discussed in light of their current ability to protect soil and water quality. Furthermore, crop and soil management practices are elaborated on, those in the NT system in particular, followed by an introduction to the emergence of farmer networks which are supporting innovative farmers such as NT farmers.

Chapter 3 outlines the conceptual framework for the study, introducing paradigms of the research methodology and the concept of agriculture as a socio-ecological system. The chapter further describes relevant concepts of the study, such as how farmers and researchers have different understandings of soil, and their different types of knowledge and learning, and ways of dealing with complexity. The concepts of ESS and soil functions are also described in this chapter. The chapter concludes with a flow chart of the PhD that outlines how the four papers (Chapter 5-8), making up the main body of this thesis, address the different research objectives.

Chapter 4 sets out the methodology, providing an overview of the theories, methods and approaches that were used to address the overall aim and objectives. The chapter justifies the interdisciplinary approach taken, explaining the need for combining methods from both natural and social sciences. A comprehensive description of the study area is also provided for the case study used in Chapter 6, as well as the methods adopted.

Chapter 5 consists of a peer reviewed paper published in the *Soil and Tillage Research Journal* titled “The effect of no-till farming on the soil functions of water purification and retention in north-western Europe: a literature review” based on recent evidence (post-2000) from north-western Europe. The paper assesses the different elements that make up a NT system (direct drilling, cover crops, crop residue management and crop rotations) and the effects on soil properties with implications for the relevant soil function. I was the lead author of this paper and responsible for the design, data collection, analysis and I led on writing the paper.

Skaalsveen, K., Ingram, J., Clarke, L. 2019. The effect of no-till farming on the soil functions of water purification and retention in north-western Europe: A literature review. *Soil & Tillage Research*, 189, 98-109.

Chapter 6 presents the results from the UK case study in a manuscript submitted for peer review to the *Journal of Soil and Water Conservation* (revised manuscript addressing reviewers comments has been submitted and is awaiting editorial decision) titled: “Impact of no-till practices on water purification and retention functions of soil”. This paper compares data collected from two commercial farms (NT and CT), assessing and explaining the soil structural properties, the soil nutrient distribution and the water quality resulting from the different systems. I was the lead author of this paper and responsible for the design, data collection, analysis and I led on writing the paper.

Skaalsveen, K., Clarke, L. 2020. Assessing the impact of no-till practices on water purification and retention functions of soil: results from a UK case study. *Soil and Water Conservation* (Accepted/in press).

Chapter 7 contains a peer reviewed paper published in *Agricultural Systems* titled: "The characteristics and dynamics of learning and knowledge exchange in no-till farmer networks" that is based on in-depth interviews and a Social Network Analysis (SNA) that were carried out with English NT farmers to contribute to evidence about farmer learning, knowledge transfer, information sources, network dynamics and information flow. I was the lead author of this paper and responsible for the design, data collection, analysis and I led on writing the paper.

Skaalsveen, K., Ingram, J., Urquhart, J. 2020. The role of farmers' social networks in the implementation of no-till farming practices. *Agricultural Systems*, 181.

Chapter 8 presents a peer reviewed paper that was published in a special issue of *Soil Use and Management* titled: "The use of Twitter for knowledge exchange on sustainable soil management". This paper is based on in-depth interviews with farmers and a Twitter content analysis to provide knowledge about the extent and type of farmer-to-farmer knowledge sharing in relation to sustainable soil management practices. Work undertaken on a separate project provided data for this study's analysis on farmer networks, complementing the SNA analysis. I designed and conducted the farmer interviews, undertook the interview analysis and contributed to the writing of the paper.

Mills, J., Reed, M., Skaalsveen, K., Ingram, J. 2018. The use of Twitter for knowledge exchange on sustainable soil management. *Soil Use and Management*, 35 (1), 95-203.

Chapter 9 is the overall discussion chapter that summarises the findings from the preceding chapters and demonstrates how the results from the four papers contribute to addressing the research objectives that were presented in Chapter 1. Further, the contribution of this research project to the socio-ecological system (SES) concept is discussed, as well as the importance and opportunities for the integration of farmer and researcher knowledge, and the complexity of soil functions and the trade-offs between them.

Chapter 10 provides the final conclusions derived from this whole thesis that reflects upon the main findings and provides recommendations for further research.

2 Background

This chapter provides context for the research in this thesis in regard to the effect of implementing NT farming systems to enhance soil functions. The first section (Section 2.1) sets the scene by providing information about the challenges relating to degradation of soil functionality, followed by an overview of the current policy landscape with respect to soil and water quality (Section 2.2). Furthermore, different crop and soil management practices and the incentives for implementing less intensive crop and soil management are described (Section 2.3), and the emergence of the information networks important for knowledge sharing about these practices (Section 2.4).

2.1 Degradation of soil functionality

Soil degradation refers to the reduction in the capacity of the soil to provide ESS and benefits due to a decline in soil quality (FAO, 2020). Soil functionality is affected by a general decline in soil quality as an outcome of human activities in combination with natural environments by the processes of chemical, physical and/or biological degradation, including SOM decline and soil loss (Lal and Stewart, 2012, Virto et al., 2014). Two key soil functions, water purification and water retention, are particularly affected by processes of degradation accelerated by agricultural production.

Chemical degradation caused by agricultural production is normally related to the overuse of plant protection chemicals and fertilizers and has the biggest impact on water quality. Two of the primary nutrients that are applied to agricultural fields are Nitrogen (N) and Phosphorous (P) (Smith, 1983, Dodds and Smith, 2016). These nutrients already occur naturally in the soil (in addition to other nutrients such as Potassium, Calcium, Magnesium and Sulphur), but additional fertilizers are normally added by farmers to enhance crop growth and development; this can be either in the form of ‘synthetic’ (i.e. artificially manufactured) or organic fertilizers.

Excess N fertilizer is lost from the soil as the mineral fertilizer use efficiency, although improving, is generally low and fertilizer application is often higher than the uptake of the plants (Galloway et al., 2008, Rani et al., 2017). Similarly, positive soil P balances resulting from external inputs and the relatively inefficient plant P uptake of approximately 60% of the total P inputs to soils has led to a rapid increase in P exported to aquatic systems (Bennett et al., 2001). N and P are also usually the limiting nutrients in fresh water systems (Smith, 1983, Dodds and Smith, 2016), and high inputs can represent a challenge to water quality and the wider environment. Water enrichment, also referred to as eutrophication, caused by diffuse pollution from agriculture is one of the main reasons for water contamination in Europe (European Environment Agency, 2018) and is caused by transport of nutrients by surface runoff or by leaching from agricultural fields. The impact of agriculture on water quality is largely determined by the agricultural management (e.g. fertilizer usage and soil tillage), the local weather, and a range of physical features such as slope steepness and soil type, specifically physical soil properties, as explored further below.

The physical properties of soils significantly impact their function within the water cycle, namely retention and purification of water flows (FAO and ITPS, 2015a). Lal and Stewart (2012) classified the physical degradation of soil as '*compaction and hardsetting*' that affect the size and occurrence of structural pores and the processes of soil densification, and '*soil erosion and sedimentation*' of topsoils that exceed the formation of new soils. This physical degradation can significantly reduce soil structure and functionality. Infiltration and the redistribution of water within and through the soil profile (hydraulic conductivity) affects the storage potential of soil water, and therefore also the proportion of water that flows on the surface as runoff with potential to cause soil erosion and transfer pollutants into watercourses.

Soil compaction reduces soil porosity and affects the air capacity, the permeability and the water-holding capacity of soils (Mueller et al., 2009), in addition to the root development and soil biological activity (Elmholt et al., 2008). This results in reduced water movement in the soil and is therefore a type of physical degradation with high implications for the water purification and retention functions. The main factors that cause soil compaction are pressure by heavy machinery and/or animals, associated with certain types of crop and soil management. The challenges with compaction increase with larger and heavier agricultural machinery and with repeated operations (Oussible and Crookston, 1992, Seehusen et al., 2014), but also depends on soil moisture content and tyre contact area (determined by the air pressure) (Seehusen et al., 2014).

The loss of structural stability is another important effect of physical degradation that can lead to a reduction in water related functions by contributing to soil erosion (Gaiser et al., 2008, Todorovic et al., 2014), and by reducing soil porosity and the water retention properties of the soil (Virto et al., 2014). There are several factors determining the erodibility of a field, both related to abiotic factors such as soil type (e.g. fine or course material) and weather (e.g. intensity of rainfall events, snow melting episodes), but also factors related to farm management decisions that are affecting important soil structural properties such as cultivation practices (Lundekvam, 2007, Knapen et al., 2007) and soil protection measures (e.g. cover crops and crop residue management) (Knapen et al., 2007, Bodner et al., 2010, De Baets et al., 2011).

The levels of organic material in the topsoil determined by historical and current soil management (FAO and ITPS, 2015a, Virto et al., 2014) are crucial for aggregate stability which is important for soil's resistance to erosion (Abdollahi et al., 2014, Frøseth et al., 2014, Elmholt et al., 2008). High erosion rates are a large contributor to reduced water quality, as the overland flow can carry both nutrients (particularly P bound to clay particles) and suspended sediments that affect water turbidity (clarity), which is another important water quality indicator. The effects of soil compaction and high erodibility combined is particularly unfortunate as increased runoff accumulation, resulting from low infiltration rates, on soils of poor structure can cause severe soil losses (Deasy et al., 2009).

The variety of the living organisms within the soil, or the soil biodiversity, is directly related to the rate of soil degradation in Western Europe (Virto et al., 2014). Loss of biodiversity in Europe is normally caused by land-use changes, intensive management and exploitation of soils, soil compaction, erosion, pollution and declining levels of SOM. The risk of biodiversity loss is particularly high in the UK, the Netherlands and Belgium, from a European perspective, where almost 100% of the land area is classified within the categories of high, very high, and extremely high risk (Gardi et al., 2013, Jeffery et al., 2010). However, these numbers are only describing the risk and not the actual loss of soil biota. The degradation processes of the soil fauna that is most crucial for the water retention functions are the decreasing activity and diversity of macrofauna such as earthworms, particularly the larger vertically drilling species (Peigné et al., 2009). These are important for the network of macropores for deep water percolation and storage (Buczko et al., 2003). Furthermore, the microfauna plays an important role in the purification process of water that is filtered through the soil profile as microbial activity drives a range of soil chemical processes (Elmholt et al., 2008, Crotty et al., 2016, Meysman et al., 2006, Gougoulias et al., 2014).

2.2 Soil and water protection policies and governance in the agricultural context

There are a number of forms of legislation and governance in place that may influence soil management in the EU and UK context. There are policies and legislation at both national (UK and its devolved nations) and EU level with the potential to enhance the water purification and retention functions of agricultural soils by reducing soil and water degradation. The emphasis is, however, normally on protecting either soil or water, which is problematic as this results in a less integrated approach to the management of these two important resources that are highly connected and co-dependent. There is more legislation aimed at protecting water quality than soil quality at the European and UK level (Paleari, 2017). Although this is enacted by addressing agricultural impacts on water quality by focusing on reducing runoff and erosion rates, less attention is paid to the synergies between soil and water and the role of healthy and functioning soils for good water management.

Two EU level directives target water pollution from agriculture: the Water Framework Directive and the Nitrates Directive. The Water Framework Directive (WFD) 2000/60/EC was implemented by the EU in 2000 to protect European water bodies and contribute to more sustainable and effective water management. This requires member states to reach at least "good ecological status" in all water bodies by undertaking the "river basin approach" which is an attempt to overcome some of the challenges mentioned above and aims to make water management decisions considering the whole catchment area for more holistic and efficient management. The WFD does not explicitly address agricultural practices or policies, but has an indirect impact as agriculture is an important source of water pollution.

The WFD builds on the Nitrate Directive 676/1991, an EU water policy implemented in 1991, which requires member states to reduce the nitrate in drinking water to a maximum of 50 mg/l, and limits the amount and timing of nitrate fertilizers applied. The overall use of fertilizers decreased in Western Europe from the year 2000 following implementation of both the Nitrate Directive and the WFD (Gómez-Limón et al., 2002), although the N and P applications vary between countries and regions, and there was a coincident increase in fertilizer prices. There has also been a general decrease in the use of pesticides resulting from the implementation of the EU Directive 128/2009 along with National Action Plans following the Directive (Jones et al., 2010), with potential benefits for the abundance of earthworms and other beneficial soil organisms.

Another European level policy that affects farmer crop and soil management decisions is the Common Agriculture Policy (CAP) providing subsidies to farmers by two payment streams; Pillar 1 and Pillar 2. Pillar 1 is the European Agricultural Guarantee Fund (EAGF) that provides payments directly to farmers (Arnott et al., 2019), while Pillar 2 supports the Rural Development Programmes (RDP) of member states and regions. The CAP has been criticized over the years for leading to intensive agriculture and overproduction harmful to the environment and has undergone a number of reforms (Berendse et al., 2004). A new CAP reform came into force in 2005 that aimed to decouple farm production from financial support to reconnect farmers to their markets and reduce damage to the environment. The financial support is now linked to cross-compliance (Posthumus and Morris, 2010) to prevent poor management and soil degradation.

At UK level both the WFD and the Nitrates Directive are implemented in agricultural policy, a set of regulatory baselines have been set, including Nitrate Vulnerable Zones (NVZs) to comply with the EU Nitrates Directive, and the CAP Cross Compliance for both directives (Table 2.1). Cross-compliance is a tool for incorporating environmental requirements into the CAP instruments to ensure the delivery of public goods, linking farm income support to EU rules. In the UK, farmers receiving subsidies under either the Basic Payment Scheme (CAP Pillar 1) or AES payments (Pillar 2) must fulfil the requirements set by the cross-compliance. These requirements are determined by the Statutory Management Requirements (SMR) and the EU standards for Good Agricultural and Environmental Condition of land (GAEC). GAEC 4, 5 and 6 provide direct requirements for the protection of soil and C stocks with conditions for minimum soil cover, minimum land management to limit erosion and appropriate practices for maintenance of SOM levels, respectively.

In England this is supported by the “Codes of Good Agricultural Practice” (CoGaP) for Soil, and for Water (Defra, 2009a) which offer a practical interpretation of legislation and advice on sustainable agriculture for farmers, such as nutrient management, irrigation regimes, crop rotations and crop types. The SMR and GAEC requirements are linked to different initiatives and approaches such as the Department for Environment, Food and Rural Affairs (Defra)’s ‘Catchment Sensitive Farming Delivery Initiative’ and the Environment Agency’s ‘Best

Farming Practices' (Table 2.1) which rely largely on advisory approaches to bring about voluntary change in practices to decrease diffuse pollution from agriculture to meet objectives set by the WFD. These have been supported by a number of research-based initiatives which have identified cost effective methods for mitigating diffuse water pollution from agriculture (DWPA) (Newell-Price et al., 2011, McGonigle et al., 2012).

Table 2.1. Overview of the regulatory, economic and advice, and voluntary instruments at EU level and their transmissions to national level.

	European level	**National level (England)**	**Recommended practices**	**Examples of Initiatives, approaches and practices promoted**
Regulation, economic and advice	CAP Pillar 1	Cross compliance GAEC 4,5,6 Codes of Good Agricultural Practice for Soil Greening measures	GAEC 4 Minimum soil cover GAEC 5 Minimum land management reflecting site specific conditions to limit erosion GAEC 6 Maintenance of soil organic matter level through appropriate practices including ban on burning arable stubble, except for plant health reasons	Defra's Farm Advisory Service – online support and workshops for cross compliance measures Best farming Practices** Environment Agency)
Voluntary	CAP Pillar 2 RDP	AES	Options: buffer strips, cover crops, over winter stubbles. Soil health, SOM reduced diffuse pollution	Countryside Stewardship Natural England support Countryside Stewardship Facilitation Fund e.g. Farmer Guardians of the Upper Thames; Carrant Catchment
Regulation, economic and advice	WFD	Cross compliance SMR1*, GAEC 12,3, Codes of Good Agricultural Practice for Water	Follow Nutrient Management Guide RB209	Defra's Catchment Sensitive Farming Environment Agency 'Think Soils'

Regulation, economic and advice	Nitrates Directive	Nitrate Vulnerable Zones Cross compliance SMR1* GAEC 1,2,3	Follow Nutrient Management Guide RB209	Defra's Catchment Sensitive Farming Mitigation Methods and Guide to their Effects on Diffuse Water (Method 7 refer to tillage intensity)**
Voluntary NGO			Different farming systems including reduced and no-tillage, enhanced SOM and soil health	Game and Wildlife Conservation Trust, Innovative Farmers, BASE
Commercial		Food assurance schemes	Accreditation and auditing of soil management practices	LEAF Marque Organic Farming Red Tractor

*SMR = statutory management requirement.

** Environment agency, 2008.

Agri-environment schemes (AES), funded through the Rural Development Programme for England (EU CAP Pillar 2) also influence management decisions in the UK and the rest of Europe. AES are voluntary and provide financial incentives for farmers to manage their land in a way that can reduce the environmental impact of intensive agriculture and contribute to reversing biodiversity losses, benefit landscape features and improve water and soil quality (Jones et al., 2017). The selection and positioning of AES is, however, decided by the farmers and therefore determined by a range of social, economic and practical variables (Mills et al., 2016). Therefore, the effect of the different management options and environmental measures is likely to vary with local environmental conditions along with farm management decisions and implementation efficiency. The emphasis of the AES has largely been on biodiversity gains (Donald and Evans, 2006, Perkins et al., 2011) with minimal attention paid to soil and water quality, although some of these relate to soil such as buffer strips, cover crops and over winter stubbles. Also, recent Countryside Stewardship Facilitation Fund activities have promoted soil health in connection with water related functions.

In the UK[1], a range of AES have been implemented since 1992 which promote environmental stewardship, providing subsidies to farmers and other land managers who manage their land in an environmentally sensitive way to protect a range of ecosystems. As a result of the UK referendum on the EU membership in 2016, the UK will move away from this two pillar payment structure towards a system where farmers are paid to deliver benefits to achieve desired environmental outcomes, often referred to as 'public goods' (Arnott et al., 2019) as set out in 25 Year Environment Plan (Defra, 2018) and the Agriculture Bill currently being debated.

There are also forms of commercial governance that can affect farmers' management of their soils. Farm assurance schemes (such as the Red Tractor, LEAF Marque, Soil Association) can provide commercial benefits to farmers if they adhere to certain conditions, and some include Soil Management Plans.

The effectiveness of these different measures, however, has been questioned. Cross Compliance GAEC standards arguably result in a "business-as-usual" approach because of their lack of specificity and enforcement (Basch et al., 2017, House of Commons, 2016). The voluntary nature of the AES limits its uptake and therefore reduces the schemes ability to deliver ESS and the government's ability to facilitate behavioural change (Bartolini et al., 2012, Arnott et al., 2019).

There is no EU-level legislative framework specifically for soil protection. The European Soil Framework Directive 2004/35/EC for the protection of soil was proposed in 2006 with the aim of protecting European soils and maintaining the sustainability of soil functions. This was the first specific legislation on soil protection at European level, but was withdrawn by the European Commission in 2014 (Official Journal of the EU: C153, 2014) as a result of a blockage by five of the member states of the EU;= (Germany, France, Austria, UK and the Netherlands) on the grounds of subsidiarity, excessive cost and administrative burden (European Commission, 2012).

A Soil Thematic Strategy (COM(2006)231) was, however, adopted in September 2006 to fill the gap in the EU legislation and provide a more holistic approach to soil protection (Chen, 2019, European Commission, 2012). However, this strategy has no regulatory authority, it relies on the integration of other instruments and has the overall objective to protect and

[1] With different arrangements for the devolved nations.

promote sustainable use of soils. The (European Commission, 2006, p. 5) states this is based on the principles of:

1) Preventing further soil degradation and preserving its functions when: (i) soil is used and its functions are exploited, action has to be taken on soil use and management patterns; and, (ii) soil acts as sink/receptor of the effects of human activities or environmental phenomena, action has to be taken at source.

2) Restoring degraded soils to a level of functionality consistent at least with current and intended use, thus also considering the cost implications of the restoration of soil.

Similarly, at the national scale, England does not have specific soil protection legislation. The Soil Strategy for England, called 'Safeguarding our Soils', was published by Defra in 2009 and builds on and replaces the Soil Action Plan 2004-2006. This outlines the Government's goal to protect soils in the long-term and supports the aims of the EU Thematic Strategy on Soil Protection, but with more emphasis on local circumstances. It focuses on areas that need attention to prevent soil degradation, primarily through enhancing the knowledge base and providing guidance to the land managers by the use of regulation and incentives where necessary (Defra, 2009b).

Scholars have discussed why efforts to provide better legislation for the protection of soil resources have been unsuccessful (Montanarella and Vargas, 2012, Paleari, 2017), and in a comprehensive report on the status of the world's soil resources the Food and Agriculture Organization of the United Nations (FAO) and the Intergovernmental Technical Panel on Soils (ITPS) (2015a) reflected on the governance and responses to soil challenges and concluded that the consideration of soils in policy formulation is generally weak in most parts of the world. Furthermore, they explained that this trend is a likely result of a combination of factors: (1) related to the access to evidence needed for policy action; (2) resulting from the complexity regarding that soils as they are (often) a privately owned natural resource with high importance for public goods; (3) as communities and institutions might not respond to critical changes in soil quality before it is too late due to the long time-scale of soil changes; and; and (4) the gap between human societies and the soil resulting from urbanization that further complicates the task of developing, articulating and implementing effective sustainable soil management.

In summary, farmers in England are subject to a range of policy instruments, economic incentives and advice that directly or indirectly influence crop and soil management decisions, and therefore soil function. None specifically promote or incentivize NT, although reduced tillage is identified, for example, as an evidenced and cost-effective method to reduce diffuse pollution (Cuttle et al., 2016), a recommendation in COGAP for Soil (Defra), and a best farming practice (Environment Agency, 2008). However, unlike some other European countries, reduced tillage is not incentivized with financial support.

Furthermore, non-policy drivers are equally important to the adoption of new and less intensive practices. Farmers are under pressure to reduce the production costs and increase efficiencies and this incentivizes them to introduce practices which reduce tillage intensity like NT that require less labour and fuel than CT (Knowler and Bradshaw, 2007). Increasing efficiencies while reducing the impact on the environment fits broadly with the Government's goal for sustainable intensification, although this is not currently incentivized by any policies or instruments in the UK. Economic, financial and institutional factors are, however, not the only drivers. Environmental factors such as the degree of soil degradation and personal factors such as attitudes towards soil conservation, knowledge and awareness of practices/technologies are all important for adoption of soil conservation practices (Prager and Posthumus, 2010).

2.3 Crop and soil management practices

Research concerning the importance of SOM, and SOC in particular, has been in the spotlight for decades (Virto et al., 2014) as this is a keystone soil quality indicator that is linked to several other chemical, physical and biological soil quality variables, and largely affected by land use. A review by Reeves (1997) assessing long-term continuous cropping systems globally confirms that years of cropping results in declining SOC levels, and that the magnitude depends on climatic factors and soil properties, but also the type of soil management and to what extent SOC is returned to the soil (e.g. by manure additions, incorporation of crop residues in the soil, or by crop rotations which include pasture or lay periods). There has been a general decrease in SOC levels globally caused by factors such as the conversion of grassland, forest and natural vegetation to arable land, intensive tillage operations, overfertilization, fertilizer use, soil water drainage, crop rotations without a satisfactory proportion of grasses, as well as soil erosion (Virto et al., 2014, Kibblewhite et al., 2008). Globally, there are approximately 1,417 billion tons of SOC stored in the first metre of the soil, while the calculated losses are around 66 billon tons of SOC since 1850, mainly resulting from land use change (FAO and ITPS, 2015a). The losses of SOC in England and Wales between 1973 and 2003 were 0.5-2 g SOC/kg soil per year (Bellamy et al., 2005).

As many of the problems related to soil degradation, such as SOC decline, are linked to agricultural management, sustainable agricultural systems such as Conservation Agriculture (that aims to minimize soil disturbance, maintain a permanent soil cover and use of crop rotations with a diversity of crop species using a variety of techniques) and organic farming (excluding the usage of synthetic fertilizers and pesticides) are being implemented as a means to overcome them (Virto et al., 2014). CT or ploughing, where the soil is turned to provide a seedbed for planting new crops (Townsend et al., 2015) has been associated with the degradation of fertile soils. Loosening and inverting the soil by ploughing is beneficial for plant growth as it causes a higher degree of oxidation and mineralisation that leads to the transition of nutrients to plant available forms. These chemical processes do, however, also contribute to increase the breakdown of organic compounds (Balesdent et al., 2000) and releasing SOC as carbon dioxide to the atmosphere from the soil C sink. The practice of ploughing also makes the soil more vulnerable to soil loss by erosion as it is left bare and unprotected by plant material (Lundekvam, 2007, Vogel et al., 2016).

Conservation Tillage is a term that describes a tillage system that aims to reduce soil disturbance, but the level of disturbance varies as summarised in Table 2.2. At the extreme end of this is NT (Table 2.1) which is a low disturbance soil management practice where the seed is drilled directly into the ground without any soil inversion (such as ploughing) (Townsend et al., 2015). NT is normally practised in combination with cover crops, that can offer soil protection and soil structure remediation (Burr-Hersey et al., 2017) and on occasion act as fertilizers (by the usage of N fixating crops, such as various clover species), by leaving crop residue as stubble to mulch and protect the soil surface (Armand et al., 2009, Todorovic et al., 2014), and by increasing the number of crop species by crop rotations. Both ploughing (CT) and direct drilling (another term for NT) have a long history, but the technique of farming mechanically using the plough became the standard for planting crops and suppressing weeds (Huggins and Reganold, 2008). Although the techniques have improved and intensified over the years they are traditionally inherited through generations.

Table 2.2. Description of types of tillage practices (although the definitions vary largely in the literature).

High ← Soil disturbance → Low

Conservation tillage

Conventional tillage	**Reduced tillage**	**Minimum tillage**	**No-till**
Moldboard ploughing Soil inversion Often followed by secondary tillage by harrows/discs	Non-inversion tillage 30 % crop residue left on the soil surface Shallow cultivation between seasons (weed control) Deep reduced tillage: depth grater than 100-150 mm Shallow reduced tillage: depth less than 100 mm	Non-inversion tillage 30 % crop residue left on the soil surface	Direct drilling Seed drilled into stubble of previous crop Often combined with permanent soil cover (residue and/or cover crops) and diverse crop rotations (also referred to as Conservation agriculture)

Low ← Soil cover → High

NT farming emerged following the Dust Bowl era from 1931 to 1939 where the southern plains of the U.S. faced a serious drought with severe wind erosion that removed the topsoil layers leaving behind unsuccessful crops and farms (Kassam et al., 2014, Huggins and Reganold, 2008). This era was the beginning of the soil conservation movement, challenging the necessity of the plough. However, this proved demanding as all aspects of agricultural production, including machinery, had to be changed to transition to NT systems. As a result of this movement, the implementation rate for NT has been the highest in North and South America (with 85% of the world's NT area), while NT globally covers less than 7% of the world's cropland (Huggins and Reganold, 2008). The uptake in Europe was substantially lower and mainly concentrated in Spain and France, partly as NT systems[2] are known to have water conserving properties that are beneficial in warmer climates. There has been increased uptake in the UK more recently given the shift towards nature-based solutions (including sustainable

[2] 'NT systems' are here referring to the whole agricultural system that often includes soil cover by crop residues and cover crops and crop rotations, which is similar to the definition of a Conservation Agricultural system. The term 'NT systems' will be used from now on as I have interpreted Conservation Agriculture as a concept and a movement with more set "rules" of practice that not all farmers identify with.

soil tillage systems such as NT), contributing to enhancing the availability and quality of water while preserving ecosystems (Sonneveld et al. 2018). In England the Environment Agency has been working with a natural processes report that aims to protect, restore and emulate the natural functions of catchments by land use recommendations (Environment Agency, 2018). Research into NT systems in Europe has been undertaken regarding benefits to farming businesses in terms of decreased labour costs compared with potential losses in yields under the system, particularly in the stages of implementation and during the first few years that follows with large uncertainties in regard to crop yields (Soane et al., 2012).

The modest uptake of NT by English farmers has been connected to the considerable uncertainty about the system (Alskaf et al., 2019), suggesting that farmers are in need of more information about this technology to overcome the difficulties. Challenges with grass weed control is another important barrier, particularly concerning grass weed species such as blackgrass (*Alopecurus myosuroides*) that has developed herbicide resistance (Soane et al., 2012, Davies and Finney, 2002). There are limited studies for the UK concerning uptake of reduced tillage (RT) and NT (Ingram, 2010, Townsend et al., 2015). RT practices (Table 2.1) are referring to cultivation systems that do not involve soil inversion, ranging from more extensive 'deep RT' to the more limited 'shallow RT' and the minimal disturbance by NT with direct drilling (also referred to as zero-tillage) (Townsend et al., 2015). The latter is the least widespread and in a farmer practice survey Defra (2010) recorded that only 4% of the total cultivated area of arable land in England was under NT, while 40% was under RT. In a study by Alskaf et al. (2019) assessing the uptake of different tillage practices they found that the uptake of RT and NT practices was relatively high in the East of England, and this was mainly associated with larger farm size, combinable cropping activities and soil type. The significance of farm size was seen in conjunction with: (i) the reduced time required for crop establishment; (ii) that the practice is still in the experimental phase for farmers, thus carries some risk, with managers of larger farms are more likely to experiment; (iii) large farms being more likely to have the opportunity to provide enough funding for investing in new machinery; and, (iv) the feasibility of larger farms having access to a larger range of machinery.

Changing from ploughing based farming to NT is not easy; it involves moving away from a farming system that has "worked" for generations and provides a certain predictability regarding the farming outcome under different years (Huggins and Reganold, 2008). By changing systems, farming becomes far less predictable and the farmer needs to learn 'how to farm' all over again by building experiential knowledge (Leeuwis and Van den Ban, 2004).

This learning procedure of transitioning takes years and farmers can experience an initial decline in yields. It is particularly challenging in terms of observing the benefits to the soil as this takes time after the implementation of a new farming system (Šūmane et al., 2018, Ingram, 2010, Lubell et al., 2014, Milestad et al., 2010). These changes in soil properties can take more than a decade before reaching a steady state. It therefore takes a long time for a farmer to experience the impact of the implementation under all possible weather conditions so that uncertainty regarding farm production can be eliminated. To speed up this 'slow learning process' farmers need to seek relevant advice, and studies show that peers are often the main source of information as farmers exchange knowledge to build on each other's experience of adapting practices to their local needs (Wood et al., 2014, Oreszczyn et al., 2010, Rogers, 2003, Dolinska and d'Aquino, 2016, Ingram, 2015).

2.4 The emergence of farmer networks

As NT is a very knowledge intensive system, and still considered as an innovative farming system in the UK, there is a need to improve the understanding of how farmers acquire and share knowledge about NT to support farmer learning. This is important since studies show an important barrier to adoption of new technologies is lack of access to information (Samiee and Rezaei-Moghaddam, 2017), potentially leading to a so called 'competency trap', meaning that the existing practices are maintained due to a lack of incentives to learn how to carry out the new practice (Eastwood et al., 2012). Scholars argue that the changing advisory landscape in agriculture in the UK reduces its ability to deliver appropriate advice to farmers about 'sustainable soil management' (SSM), such as NT (Ingram and Mills, 2019). The demand for, and type of, information that farmers require is changing and increasing in complexity with the transition to SSM. Ingram and Mills (2019) argue that the changing context limits the advisory services ability to address the current and emerging knowledge needs by these practitioners. They point the organization of the agricultural sector (moving towards increasing intensification and specialisation), the change in the farming population (an increasingly complex management landscape of owners, tenants, contractors, partnerships etc. affecting the willingness and opportunities for SSM), the fragmented policy landscape at both EU and national/regional levels, and the transformation of advisory services with increasing privatization (potentially leading to a lack of investment in environmental knowledge), which impinges on advisory services for SSM. In this context, the importance of farmer to farmer learning to implement new practices is key (Ramirez, 2013), along with incentives for such practices that are currently lacking (outlined in Section 2.2).

Understanding the effects of a 'new system', such as NT, on different soil types and management on different spatial and temporal scales requires long-term facilitation of farmer experimentation and learning. Scholars suggest that advisers should be offered training in initiating, fostering and brokering farmer networks to support the uptake of SSM, and integrate knowledge from farmers, advisers and researchers for best practice. More knowledge about the nature of farmer networks and how information is distributed between farmers is essential to increase the information flow between farmers. Furthermore, as farmers' values and knowledge are important to achieve more SSM, understanding the different approaches to knowledge exchange and learning between farmers is crucial. Farmers are an important repository of knowledge about NT which has been largely untapped.

To support NT farmers, but also researchers, advisers and policy makers, in the UK, more evidence about the effects of NT practices on soil functionality is necessary. The objective of this study is therefore to assess the effect of NT on the specific soil function of water purification and retention, both by reviewing recent literature from NW Europe and by producing and analysing data from a UK case study (see Chapter 4). The results will provide a knowledge base for evaluating the suitability of NT in areas with similar climatic conditions as the UK (as these are underrepresented in the total body of knowledge about NT) and contribute to knowledge by delivering results comparing the ability to deliver this function by both a NT and a CT system. To further support NT farmers, researchers, advisers and policy makers, understanding their information and learning systems is crucial, hence the analysis of farmers' engagement with social networks and the potential of these networks for information flow, knowledge exchange and learning between farmers. In order to address these objectives, an interdisciplinary approach is needed as this study aims to contribute to evidence both to the natural science disciplines of soil and water research, and to the social sciences regarding farmer learning. This will be addressed further in the following chapter (Chapter 3) that will set out the context and conceptual framework for this PhD study.

3 Conceptual framework

3.1 Conceptual framework: dealing with complexity

As described in Chapters 1 and 2, the underpinning rationale for this study is to enhance understanding of SSM to improve soil and water quality. This requires an approach that captures both the natural and human dimensions of the problem as soil functions are ultimately about human wellbeing (Schulte et al., 2014). Specifically, the approach needs to achieve the two key objectives: to understand the effects of different crop and soil management practices on soil functions and, to investigate the nature of information flow and knowledge exchange between farmers, and the dynamics of farmer networks. As such it requires an appropriate framing, research design and methodology and conceptualisation to address both objectives and more importantly the relationship between them.

3.2 Paradigm and methodology

Soil science and social science disciplines are underpinned by different research paradigms (Mackenzie and Knipe, 2006, Scotland, 2012). These are theoretical frameworks which influence the way knowledge is studied and interpreted, setting the intent, motivation and expectation of the study (Mackenzie and Knipe, 2006). A paradigm consists of the three elements of: ontology (the study of being); epistemology (the nature and forms of knowledge); and methodology (the plan or strategy of action determining the choice and use of particular methods) (Scotland, 2012). A paradigm dictates the literature consulted and the research design and can be defined as the philosophical motivation for undertaking the research.

Positivism and interpretivism/constructivism are two main theoretical paradigms. The positivist paradigm (also referred to as the scientific paradigm) has the ontological position of realism, believing that objects have an existence independent of the observer (Cohen et al., 2007). The epistemological position of positivism is objectivism, discovering absolute knowledge about an objective reality with the researcher being independent from the research

(Scotland, 2012). The positivist methodology aims to explain relationships as a basis for prediction and generalisation (see Creswell 2009) and methods often generate quantitative data and analysis that are used for studying the natural world (Mackenzie and Knipe, 2006). The relationships between variables or among treatments are often tested by hypotheses and assessed using instruments, observations or documents that yield numerical data (Creswell, 2003).

The interpretivist/constructivist paradigm has the ontological position of relativism and views reality as individually constructed and varying between different people (Guba and Lincoln 1994). The epistemology of interpretivists is subjectivism and is based on real world phenomena (Scotland, 2012) by understanding the world through human experience (Cohen and Manion, 1994). The interpretive methodology aims at understanding phenomena from the individual's perspective, using grounded (inductive) theory generated from the data (Scotland, 2012). The social world is complex and cannot easily be measured or generalised and interpretive methods therefore aim to provide insight and understandings of behaviour and actions from the perspective of the individuals (Scotland, 2012). Interpretive methods often yield qualitative data that is more exploratory and with a thematic focus on understanding a central phenomenon through procedures such as interviews, observations, documents and audio-visual materials (Creswell, 2003). Constructivist research relies mostly on qualitative data collection methods, but can also use a combination of qualitative and quantitative research methods (mixed-methods) (Mackenzie and Knipe, 2006).

Given that SSM is determined by the interactions between the biophysical dimensions and human management, a distinction is often made between scientific and non-scientific forms of knowledge in the farming and soil management context (Ingram, 2010, Bourne et al., 2017, Schneider et al., 2010), leading to methodologies that draw on different epistemologies. Typically, quantitative approaches are more suited to understanding codified scientific knowledge about soil processes, and qualitative methods more suited to understanding informal tacit knowledge generated and shared by farmers. This distinction has been critiqued however as the interactive amplification of the two forms can enhance knowledge (Jasimuddin 2005, Nonaka 1994) and that the two are inseparable as knowledge is constantly shifting between the formal (scientific) and the informal (tacit) forms. Here mixed-methods can provide a more nuanced understanding of different knowledge processes.

As this study seeks to understand both the physical effects of soil management on soil function alongside the social networks within which knowledge is circulated and management decisions are made, it draws on both interpretivist and positivist paradigms, therefore requiring an interdisciplinary approach. As such, a range of methods are utilised, including both quantitative and qualitative approaches to generate new knowledge and an improved understanding of both the environmental and human factors involved in the resource system of agriculture. Mixing methods has become more common and accepted in recent years as approaches to research have become more flexible in the application of methods (Creswell, 2003). Many researchers have started to see qualitative and quantitative methods as complementary and an approach that can enhance the research (Mackenzie and Knipe, 2006) by strengthening the research claims as they are based on a variety of methods (Gorard, 2004).

3.3 Agriculture as a complex Socio-Ecological System

This research aims to understand and link natural and human processes. The Socio-Ecological System (SES) framework, or human-environment system, provides a useful overarching understanding or framing for this study as agricultural systems are combinations of the natural environment and the people who are managing it. SES is a commonly used framework that attempts to understand the relationships between ecological and social processes across disciplines (Cote and Nightingale, 2011, Ostrom, 2007, Ostrom, 2009, Dwyer et al., 2018), offering insights that cannot be gained when these systems are viewed separately (Campbell, 2005). SESs have a high level of complexity and to understand the processes of use, maintenance, regeneration and destruction of the natural resources within such a system, insight into a wide variety of processes that are occurring either simultaneously or sequentially is necessary and requires cooperation between different scholars (McGinnis and Ostrom, 2014).

Ostrom (2009) suggested a multilevel, nested framework for accumulating knowledge and analysing the likelihood of self-organization in efforts to achieve a sustainable SES. This framework provides a common set of relevant variables to be used by different disciplines that would otherwise operate with different frameworks, theories and models to facilitate inter/multidisciplinary efforts. Therefore, SES frameworks have been compiled to assist researchers to work across inter/multidisciplinary boundaries and to improve communication across disciplines and understanding the determinants of sustainability in complex SESs (Bodin and Tengö, 2012, McGinnis and Ostrom, 2014). The different scholars involved in the analysis of complex, nested systems like SES all have different technical languages and therefore need to develop a common vocabulary and a logical linguistic to improve communication (McGinnis and Ostrom, 2014). Such an interdisciplinary framework can provide a scientific dictionary for core concepts and their sub-concepts that will facilitate more efficient collaboration of multidisciplinary teams of researchers (McGinnis and Ostrom, 2014).

Exploring the effect on socio-ecological outcomes and human behaviour over time is key to understanding the scenarios that lead to more sustainable and productive use of resource systems and the scenarios that can cause resource collapse (Ostrom, 2007). Rivera-Ferre et al. (2013) applied the SES framework to an agricultural setting characterizing agriculture as a complex SES that expresses certain human-environment interactions in a dynamic process that is shaped by errors, uncertainty, learning and adaptation. They call for a more holistic thinking instead of relying heavily on controlled field trials for hypothesis testing that overlooks the advantages of process analysis for explaining the state of the system. The concept provides an evaluation framework of social and ecological implications on political decisions and development while introducing different perceptions of reality by different stakeholders. It also offers a means for integrating different types of knowledge which are required for complex systems, and inter- and trans-disciplinary collaboration to enable the adoption of multiple perspectives, levels of organization and scales (Rivera-Ferre et al., 2013). This is illustrated by the adapted figure of SES-based land degradation neutrality interventions framework developed by Okpara et al. (2018) (Figure 3.1). The SES introduces the principles of learning, flexibility, adaptation, scale matching, participation, diversity and precaution (Ostrom, 2007, Ostrom, 2009) that are factors that could significantly improve the current standard management procedures (Rivera-Ferre et al., 2013, Okpara et al., 2018).

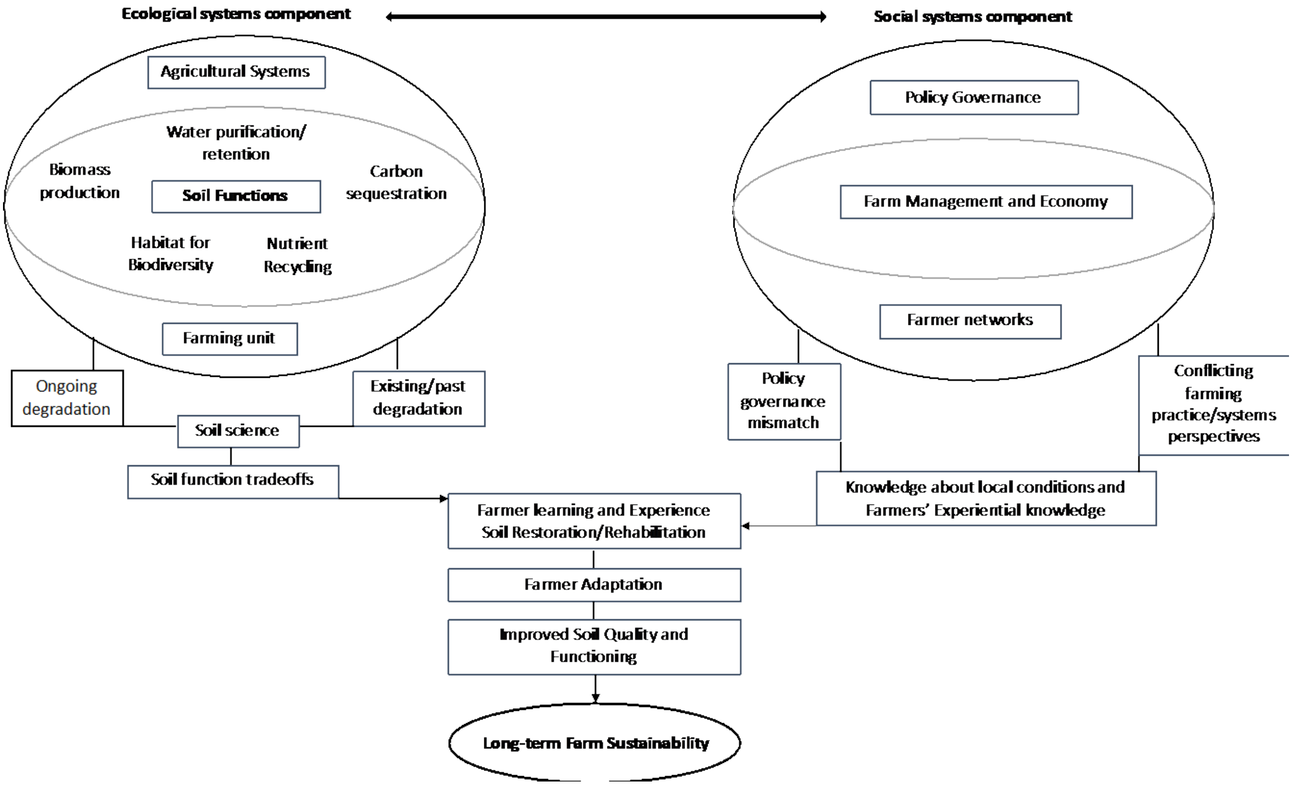


Figure 3.1. Agriculture as a complex SES adapted from a SES-based land degradation neutrality interventions Framework by Okpara et al. (2018).

This concept is suited to framing the research approach in this thesis because it investigates potential changes from one agricultural system to another, resulting from a desire from local and endogenous driving forces to maintain good soil and water quality, and is therefore an example of 'socio-ecological feedback'. This is one of the most important mechanisms driving land use transitions, in addition to socio-economic change (Lambin and Meyfroidt, 2010). Socio-ecological feedback means that the land use transition is associated with a negative feedback that arises from a depletion of key resources resulting from a severe degradation of ESS from the past management practices (Lambin and Meyfroidt, 2010). The transition to new farming systems, such as NT, is not necessarily a result of 'severe degradation' (as stated by Lambin and Meyfroidt, (2010), but rather the result of a need recognised by the farmer to alter the system to prevent soil degradation (Milone and Ventura, 2019). The boundaries of a SES are directly involved in the transition and key to this is the area that is being changed and the people living there, demonstrated by the adapted SES framework shown in Figure 3.1. This framework illustrates that the SES is a complex adaptive system with the two main subdomains of 'soil functions' on one side and 'farm management and economy' on the other, coupling the ecological and social systems components to give insight about trade-offs and synergies between these two components across scales.

This offers a platform to integrate different views and dimensions of changes in soil function delivery as a result of land use. The framework consists of different subsystems and variables that interact within a dynamic structure that facilitates interdependencies and feedback, that are all important to analyse the SES (Okpara et al., 2018). To achieve long-term farm sustainability the outputs from the ecological and social dimensions should be integrated to enhance farmer learning and experience about restoring soil function, that will trigger increased uptake of such practices (Krzywoszynska, 2018) and lead to improved soil quality that promotes soil functions.

3.4 Conceptual framework for this research

Figure 3.2 illustrates the conceptual framework for this PhD study and outlines how the two disciplines of soil and social science are being approached to combine the science-based evidence and farming communities' different ways of knowing and understanding of soil in an interdisciplinary analytical framework. This complexity plays out at different scales and has implication for those involved, particularly with respect to evidence.

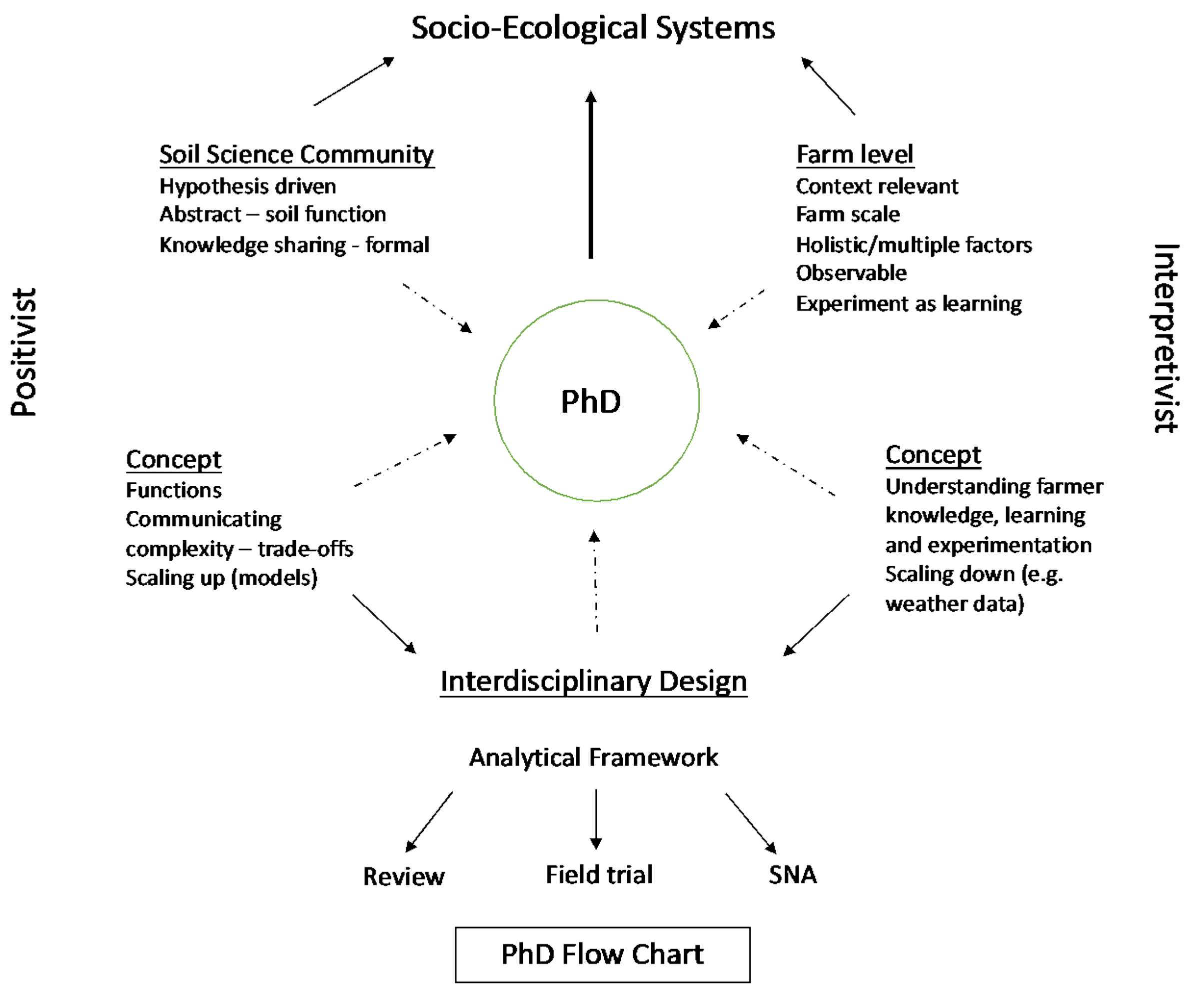


Figure 3.2. PhD conceptual framework demonstrating the combination of positivist (physical science) and interpretivist (social science) approaches that will be utilised and combined in the complex SES and interdisciplinary design of this PhD.

3.5 Concepts

3.5.1 Different understandings of soil

Differing modes of examining and understanding soil and sharing knowledge in the soil science community and the farming community are underpinned by positivist and interpretivist paradigms respectively (see Section 3.1). These paradigms and the two communities are represented by the different sides (left and right) of Figure 3.2. This also presents the different ways of knowing and learning, dealing with complexity, and conceptualizing soils that will be further examined in the following sections. From the context of understanding soil management impacts, these natural and social processes of the SES are manifested in the way that the soil science and farming community respectively measure, perceive, experience them.

3.5.1.1 Knowledge and learning

The two communities (soil science and farming) generate, share and disseminate knowledge in different ways (Ingram, 2010). A distinction is often made between scientific and non-scientific forms of knowledge in the farming and soil management context (Ingram, 2010, Schneider et al., 2010, Bourne et al., 2017), which are underpinned by different epistemologies. The nature of knowledge can be distinguished by two types of knowledge, tacit and explicit (Nonaka, 1994, Jasimuddin et al., 2005). Tacit knowledge is deeply embedded in people's actions, commitment and involvement in a particular context and has a personal quality that can be challenging to formalize (Nonaka, 1994). This type of knowledge has both technical and cognitive elements where the technical elements refer to the know-how, crafts and skills to apply to a certain situation or context, while the cognitive dimension is more related to the perspectives of the individuals that help them define their world (Nonaka, 1994, Nuthall and Old, 2018). The explicit knowledge is more discrete or digital, meaning that it exists in the formal format of libraries, databases and archives, for example in the form of scientific theories published in documentation (Hislop, 2002). The science community has a formal (explicit) codified form of sharing knowledge that is often communicated in a systemic language based on theory and rationality (Nonaka, 1994). Scientists generally base their knowledge on the formal information that exists within the science community which originates from various studies and experiments.

Farmer learning is a social process where actors are connected by social ties in interpersonal networks (Oerlemans and Assouline, 2004, Cadger et al., 2016, Isaac, 2012). The constant need for new knowledge within the community is an important driver for new innovations (Lubell et al., 2014, Wu and Zhang, 2013), and an important characteristic of farmer networks is the sharing of tacit or experiential knowledge that is generated through individual farm experimentation (Leeuwis and Van den Ban, 2004). Farmers often view their peers as their most important source of information (Wood et al., 2014), and this type of informal (tacit) knowledge exchange by social learning is particularly important in the transition towards the implementation of new farming practices.

3.5.1.2 Dealing with Complexity

Understanding the impact and dynamics of different farming systems is incredibly complex because of the uncontrolled spatial and temporal variability in the natural landscape and the multifaceted nature of farming (Cook et al., 2013). Each of the soil functions embodies a complex set of biogeochemical processes that vary with soil type and land use combinations (Schulte et al., 2014), but can also vary within fields as soils can be highly heterogenous. The spatial variability that is present in agricultural systems can differ between different soil properties and is related to a combination of land use patterns and chemical, physical and biological processes, but is still poorly understood (Peukert et al., 2012).

Scientific and farming communities have different responses to, and understandings of, this complexity (Rivera-Ferre et al., 2013). The scientific community is hypothesis-driven with the aim to understand complexity by separating the effects of different treatments and variables from small scale from field samples or plot experiments (Bouma et al., 2008). Upscaling processes based on this data is an important issue in land use studies and often carried out by complicated models or extrapolation methods that predict the impact of these complex patterns on larger areas, such as a field, catchment, landscape or for a whole country (Bouma et al., 2008). For farmers, the opposite challenge of scaling down often applies (e.g. implication of regional land use phenomena or weather forecast data for the individual land user). They operate on a field or farm scale (Bouma et al., 2008) with a holistic approach that focuses on the total impact of the multitude of factors that are all affecting the farming outcome (Baars, 2010, Šūmane et al., 2018). They observe the effects of their practices or any ongoing experimentation on the farming system under different site specific contexts, with differing weather and field conditions (Baars, 2010).

As well as scale, there are differences in how scientists and famers conceptualise complexity and system interactions (Yageta et al., 2019). Scientists draw on abstract concepts, such as soil functions, and model or quantify trade-offs and synergies between them, while farmers tend to weigh up the potential outcomes on a whole farm basis integrating formal knowledge with observations, experience, rules of thumb and perceptions of risk (Nuthall and Old, 2018).

To further decrease the gap between formal science and farmers a better understanding of their knowledge processes is necessary. This study can feed into and adapt the SES framework by providing an enhanced understanding of how these communities can support each other in the context of NT implementation. In that way, the complex interactions and trade-offs between soil functions can be viewed in combination with farmer experience for holistic and sustainable management that benefits both the farmer and the society. These trade-offs may occur between ESS/soil functions when the provisioning of one (or more) service or function inhibits the provision of others (Gissi et al., 2018).

3.5.2 Conceptualising soil function

The first objective of this study is to understand the effects of CT and NT on soil functions. Soil function (together with soil ESS) is an abstract concept (see Section 1.1) used by soil scientists to understand soil processes and to place value on the role soils play in sustaining the wellbeing of humans and of society in general (Bouma, 2014, Haygarth and Ritz, 2009, FAO and ITPS, 2015b). The soil resources have a crucial role in delivering ecosystem goods with a multi-functionality that supports various regulation and production functions of great social and environmental importance (Greiner et al., 2017).

Schulte et al. (2014) introduced the concept of Functional Land Management (FLM) where the supply and demand for soil functions is incorporated to optimise the multi-functionality of soils and land use at local and national levels. The soil functionality will vary with variables like farm management, soil type and local weather, meaning that, for example, a farm practice under certain conditions might improve the water quality, but at the same time increase the total greenhouse gas emissions. It is possible to enhance more than one soil function at a time, achieving benefits to both the environment and production (Valujeva et al., 2016). The interaction of the different soil functions can however impede ambitious targets for separate functions (Valujeva et al., 2016). The multi-functional demand on land and possible trade-offs between targets should therefore be considered (Valujeva et al., 2016) and more knowledge about the effect of different farming systems on separate functions is therefore important, and the reason why this study focuses on the water purification and retention function of soil.

3.5.3 Conceptualising knowledge exchange between farmers

The second objective of this study is to understand the nature of information flow and knowledge exchange between farmers and the dynamics of farmers' networks in relation to the effect of different crop and soil management on soil function. There are a number of approaches to theorising farmers' knowledge exchange processes, these tend to cohere around the concept of networks.

Sharing a common goal and identity is one focus of network conceptualisation. Communities of Practice (CoPs) are defined as a group that forms a community with a common identity and interaction by sharing a common pursuit, activity or concern (Morgan, 2011, Tran et al., 2018). Networks of practice (NoPs) similarly are bound together by shared know-how, culture, practice and activities but are distributed businesses with looser connections (Brown and Duguid, 2001). Members of a NoP may never meet or know each other yet they share a common culture and activities and are capable of sharing knowledge and identity (Brown and Duguid, 2001). Farmers' participation in networks and a shared identity can increase their commitment to particular ideologies and practices (Gray and Gibson, 2013). CoP frame farmers in networks as social learners (Morgan, 2011) but learning is situated and understood as a collective experience with activity (not the individual) being the unit of analysis (Oreszczyn et al., 2010, Wenger, 1998, O'Kane et al., 2008). Similarly Dolinska (2011) places the emphasis on the practice dimension, describing networking as interpersonal practice.

Other commentators pay attention to how farmers draw on different sources and types of knowledge (Curry and Kirwan, 2014). Eastwood et al. (2012) linked social learning to the dynamics of farmer learning networks in the use of Decision Support Systems (DSSs). They found that DSS required explicit knowledge but that integrating it into the farm system was highly tacit-knowledge driven since the farmers preferred to learn from informal sources and base decision-making processes on tacit knowledge, meaning context-specific experimental knowledge that is often used intuitively and subconsciously. The informal sources, referred to as 'networks of known contacts' had similarities to the "web of influencers of practice" suggested by Oreszczyn et al. (2010), referring to a wider group of people and organisations. However, while both concepts highlight the role of tacit rather than explicit knowledge, Eastwood et al. (2012) found that the ability to interact with other farmers and farmer support networks was crucial for successful uptake of new technology, whereas Oreszczyn et al. (2010) found other trusted actors to be more influential.

Social capital has also been used as a lens through which to understand networks (Kilpatrick and Falk, 1999). Farmers' socio-spatial knowledge networks (SSKNs), combining farmers' explanatory mental models of their acquisition and use of information with a micro-geographical analysis of the social relationship networks, were mapped by Sligo (2005). The method draws on the formation of social capital, defined as the collective social resources available to individuals in the form of networks of relations or connections that may be used to access other resources, coping mechanisms and general livelihood strategies, within communities via interpersonal linkages (Sligo, 2005). Her findings, which show the importance of interpersonal sources of information, that could be both on and off the farm and dispersed widely, are in line with those of Oreszczyn et al. (2010). Sligo and Massey (2007) considered how interpersonal social networks were mediated through risk and trust, which is in line with Carolan (2006), who examined the way that social relations of trust and knowledge are shaped and contested within and between agricultural social networks. They also note the importance of not isolating informal social relations from the more formal (Sligo and Massey, 2007).

Other researchers have conceptualised network building, referring to different paradigms. Wu and Zhang (2013) explored information transfer between farmers in the form of farmer innovation diffusion (FID), defined as a process of diffusing farmer innovations to wider communities by building collaborative communication and cooperation networks between farmers, governments and other stakeholders. The study showed that mutual trust between farmers' leaders and other community members and between farmers and local governments were core elements. FID could be seen as a process of collaborative network building affected by whether they were informal networks built by farmers, farmer-led networks or government-facilitated networks. Schneider et al. (2012) drawing on actor network theory describes NT development in Switzerland as a dynamic process of co-creation of innovation in which there is a relational process of network building, in which the actors co-evolve with the innovation they have generated.

This chapter has described the conceptualization and the framing of this PhD-project. This captures both the natural and human dimensions of the problem which is required to achieve the objectives. Following on from this, the next chapter will provide more detail of the positivist and interpretivist methodologies and the methods used to address the four research objectives.

4 Methodology

This chapter provides an overview of the theories, methods and approaches used to address the overall aims and objectives of this PhD project. The chapter begins by explaining the choice of an interdisciplinary approach for this project and the justification of combining different scientific disciplines (section 4.1), followed by an introduction to the methods that were used at different stages of the project (section 4.2) grounded in both natural and social science traditions and theories.

4.1 Interdisciplinary approach

This study builds on both positivist and interpretivist methodologies by combining natural and social science disciplines in an interdisciplinary project design. Furthermore, it addresses an issue of SSM at the nature-practice interface. Sustainability is a central driver for interdisciplinarity, as it requires an approach that can address the gaps between knowledge and management (Okpara et al., 2018, Miller et al., 2008). Multidisciplinary research differs from interdisciplinary research by maintaining disciplinary boundaries by not integrating the disciplines or researchers with different backgrounds, but rather investigating the problem separately and integrating later by 'stapling together' the individual findings. This approach is referred to as comprising "epistemological siloes" (Miller et al., 2008). Interdisciplinary research, synthesising more than one discipline, has a higher degree of integration and is often motivated by the recognition that more than a single way of knowing is necessary to understand the complexity of the world (Miller et al., 2008). This thesis aims to integrate different types of knowledge conceptualised in the SES framework (Figure 3.2). Scholars have argued that the privileging of single epistemological perspectives could potentially limit the potential variety of scientific and local knowledge that can contribute to our understanding (Miller et al., 2008).

The application of the SES as an overarching framework is a means for this PhD to avoid a disciplinary 'silo approach' by providing a frame for introducing and discussing the social and ecological dimensions together. The decision to publish the results chapters as papers did however complicate this as interdisciplinary papers can be difficult to publish (although an increasing number of journals are claiming to be interdisciplinary they tend to have a disciplinary ‘home’). Due to the time limit of the project the decision was made to separate the results from the different disciplines into different papers to reduce the risk of paper rejections. The presentation of the thesis is therefore partly multidisciplinary although I have adopted an interdisciplinary approach. Another central challenge to interdisciplinary research is often that social and natural scientists approach research from different paradigms (outlined in Section 3.1) and ontological and epistemological perspectives which can be a hindrance (Campbell, 2005) as a single researcher always has a disciplinary “home” that they favour. This challenge applies to this one-person PhD project as my disciplinary “home” is within the natural sciences, therefore requiring more effort in building in-depth understanding of the social sciences to connect the two. A drawback of the interdisciplinarity of the project is the reduced time available for data collection for each of the disciplines (i.e. less time for field work and analysis and/or for interviewing farmers), that can lead to a feeling of inadequacy within both fields.

There are, however, benefits to carrying out two different disciplines of science at the same time, by achieving experience with integrating the different types of knowledge and exploring how these different “layers” of complexity can complement each other and help to achieve a deeper, more holistic understanding of the topic under investigation. Undertaking and integrating a new discipline has been a challenging but rewarding journey. Becoming an interdisciplinary researcher has been a long process that has lasted over the duration of the project and I believe that reflecting on the strengths and weaknesses of both disciplines has had great implications for my development as a researcher. Viewing my “home” discipline from a different angle and reflecting on what I have gained in terms of knowledge and insight from combining my positivist quantitative field data with in-depth understanding of the issue from interpretivist qualitative analysis has been a highly valuable lesson.

4.2 Methods

The project consisted of three different phases as illustrated by the flow chart (Figure 4.1). The methods that were used in this study are explained briefly in the following sections and further described in the Chapters 5, 6, 7 and 8 (in the methods sections of the four papers).

The structure of this thesis evolved from the conceptual framework (Chapter 3) and is illustrated by the flow chart in Figure 4.1. The field monitoring was carried out on two individual commercial farms to investigate the effects of CT and NT on soil functions at different temporal and spatial scale (outlined in Section 4.2.2). This on-farm operational research approach was applied to increase the relevance for the farmers, requested by the farming community as they were interested in exploring if the changes they noticed in the soil could be “proven” by soil science. To improve our understanding of farmer knowledge and learning, a study of the social networks of NT farmers in England was carried out by using a mixed-method design consisting of semi-structured interviews and a SNA (outlined in Section 4.2.3).

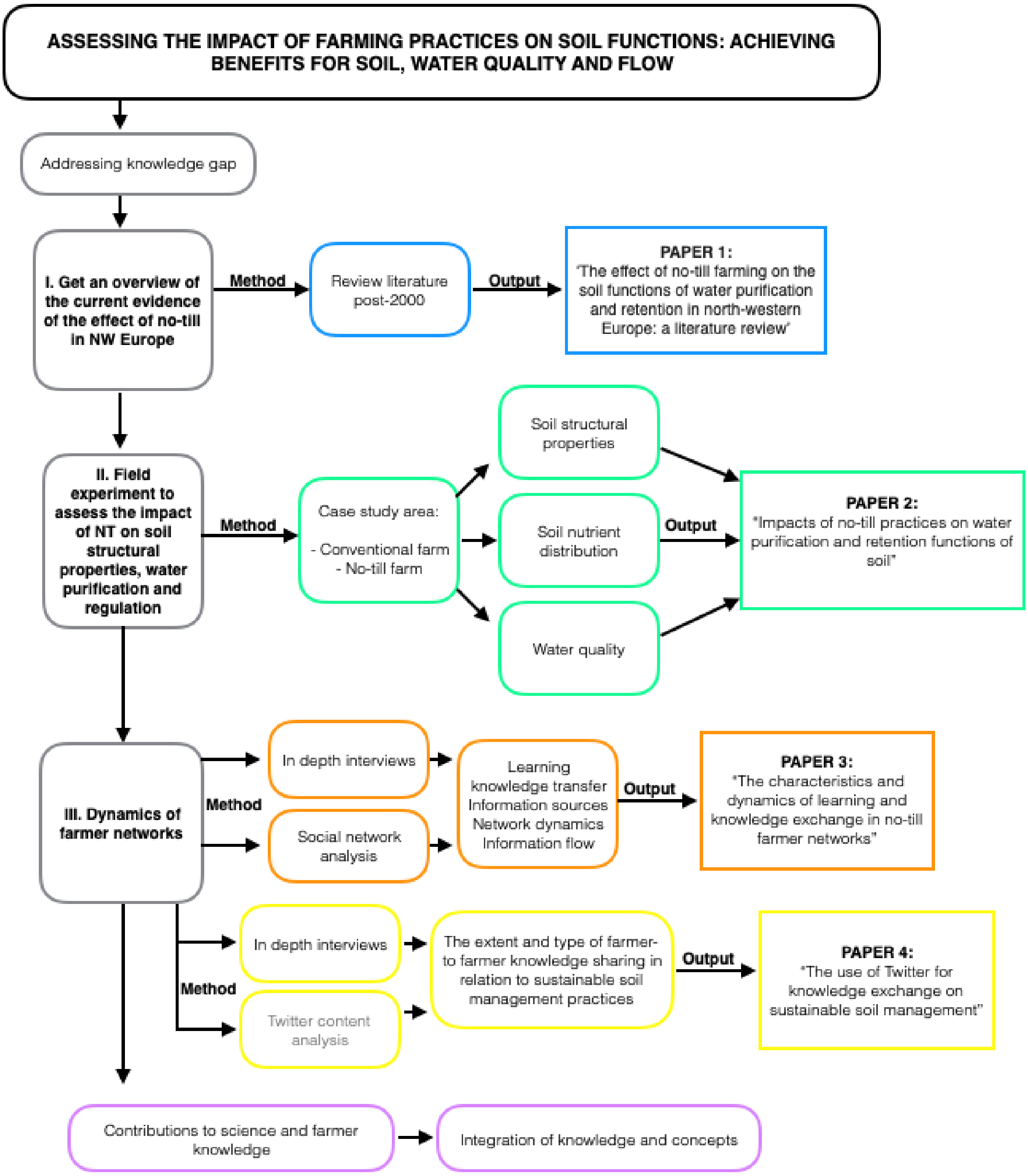


Figure 4.1. PhD Flow Chart.

4.2.1 Literature review

The methods used in the first phase of the PhD project were designed to address the first objective: "to create an overview of the current knowledge on the effects of NT practices on soil functions in Europe, with a particular focus on the water related soil functions of water purification and regulation”. A literature review was conducted based on recent (2000-2018) literature and was restricted to papers that originate from NW European studies and refer to research on the following practices which are associated with NT principles: non-inversion practices (also referred to as NT, zero tillage or direct drilling), soil cover, cover crops, soil residue, mulching, crop rotations or intercropping (one or more of the listed) in order to narrow down the result to the most relevant papers. The reason for setting the geographical boundary to NW Europe was that there is already a large body of literature with evidence from countries with more arid climates than this region that show positive effects of NT practices, however the results from these countries might not be transferable to the primarily oceanic climate in NW Europe (Peel et al., 2007).

The review focused on the soil function of water purification and retention as an assessment of all soil functions would be too demanding for the scope of this PhD project. The methods that were used for conducting the review are detailed in Chapter 5, and the findings from this review put forward recommendations which contributed towards the methods and knowledge in the subsequent PhD phases.

4.2.2 The effects of no-till

A core element of this PhD project was to achieve the objectives to:

- “establish a monitoring programme for collection, analysis and interpretation of soil and water data to assess long-term effects of NT practices on water related soil functions” and to;
- “assess the applicability of NT as a sustainable practice in the UK and its potential to enhance soil properties and specifically the soil functions of water purification and retention by evaluating the overall effects of shifting from conventional practices to NT”.

The methods adopted to address these objectives are set out in the following sections.

4.2.2.1 Case study area

This study evaluated NT and CT fields at Bredon Hill in Worcestershire, UK. The case study area (see location map in Chapter 6) consisted of four fields distributed between two neighbouring farms (Table 4.1), one under a NT and one under a CT farming system, and two different soil types under each farming practice: a free-draining porous limestone called 'Cotswold brash' and a lime-rich loamy soil with high silt and clay content (Figure 4.2). The area was selected due to the unique opportunity to assess the performance of different farming systems on very different soil types as both farms are located on a hillside consisting of coarse textured soil types on the top and finer textured soils further down the slope. Therefore making it possible to distinguish between the effects that were caused by the farming systems and those caused by the soil properties. Further details about the four study fields can be found in Chapter 6.

Table 4.1. Overview of the four case study fields: NT-S, NT-C, CT-S and CT-C.

	Soil types:	
Farms:	**Cotswold brash**	**Lime-rich loam**
NT	NT-S	NT-C
CT	CT-S	CT-C

The NT farmer is a member of LEAF (Linking Environment and Farming), and made significant changes in land use by implementing RT in 2013 followed by a conversion to a NT system in 2015. The farm manager has therefore shown great interest in validating his observations after the conversion with scientific data. The CT farm was selected as this is the neighboring farm so that the two areas are comparable with regards to soil type and topography and could therefore be compared on the basis of agricultural management systems. The approach to engaging with and interviewing the case study farmers started by undertaking formal interviews to conduct information about the farms, the farming systems and the different soil types and crop rotations. These interviews were carried out to inform the research design decisions so that appropriate fields were selected and suitable methods employed, and to provide understanding of their choice of farming system. As the project evolved my relationship to the farmers became increasingly informal as I would meet them when carrying out the field work, and knowledge and information was shared and discussed through day-to-day conversations in addition to more formal meetings.

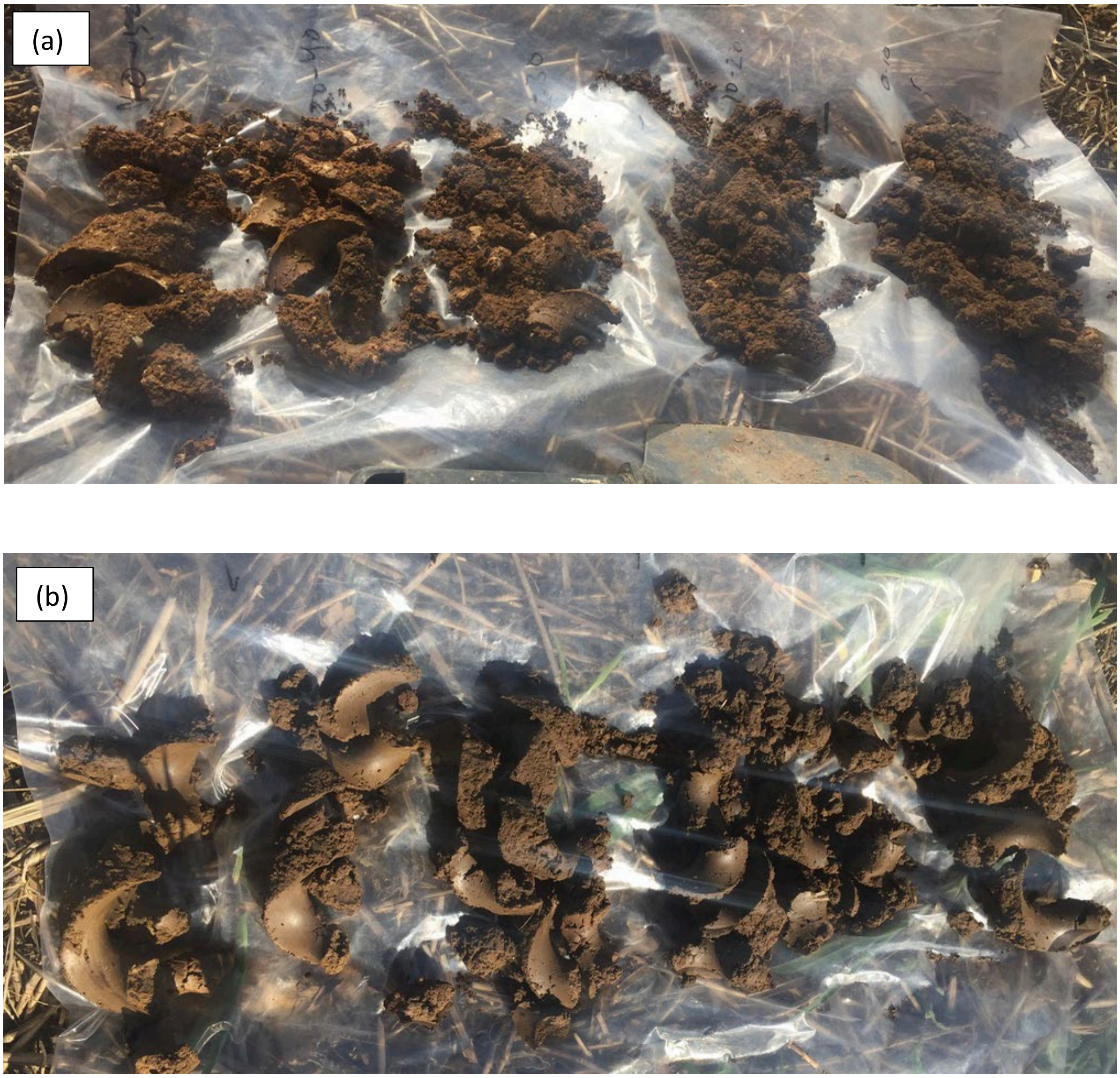


Figure 4.2. Pictures of samples from 0-50 cm (shallow to deep soil from right to left) from the two different soil types: a) Cotswold Brash soil, and b) the lime rich loamy soil.

The farms were both commercial farm businesses, therefore there were no controlled trials with replicated experimental design, but rather an ongoing field level monitoring of two fields on each farm. Controlled experiments are both expensive to establish and not always trusted by the farmer as they do not reflect a "real system". This was supported by Cock et al. (2011) who stated that the outcome from a certain type of management is a result of the complex interactions between several factors interacting with each other. The operational on-farm research approach cannot explain a large proportion of the variation in the findings (Cook et al., 2013), but is more relevant and applicable to farmers (Thomas et al., 2020). However, this has to be balanced against the requirement for statistical validation and rigour demanded by the scientific method. Assessing a commercial system requires a different set of methodologies and analysis than for traditional agricultural research (Cock et al., 2011). Cook et al. (2013) suggested that on-farm experimentation has the potential to encourage scientists to bridge the boundaries between formal science and farming practice, and in that way reduce management uncertainties and help farmers to make good and informed decisions (Chambers and Jiggins, 1987, Krzywoszynska, 2018). Although this study comprises monitoring and not strictly on-farm experimentation, these points are still valid.

The NT farm for this study had already implemented the practice when the monitoring started, so there is limited baseline data to be able to analyse field data before and after NT. However, exploring the differences between the two farms can provide an indication of the different effects of implementing the NT system in the area, with the CT farm as a proxy control, although it cannot be directly treated as baseline data.

4.2.2.2 Field sampling and assessments

Soil and water samples were collected from the four fields to assess the impact of NT on variables selected as they are indicative of the water purification and retention soil functions; the nutrient content, soil physical variables and water quality (Table 4.2). Monitoring was undertaken from 2015 to 2019 (the sampling from 2017 to 2019 was within this PhD), with more detailed soil sampling and field measurements undertaken in the Spring (April and May) and Autumn (September and October) of 2018 and the Spring (March, April and May) of 2019 (detailed in Table 4.2). In Spring 2018 a more detailed sampling regime was implemented, with sampling of every 10 cm of the soil profile down to 50 cm depth (the maximum achievable depth given the soil conditions) to determine if there were any differences in the distribution of soil functions within the soil profile under NT and CT. An overview of the different field soil and water sampling, laboratory analysis and statistical analysis that were carried out throughout the project can be found in Table 4.3.

Table 4.2. Overview of the annual monitoring strategy for soil and water sampling that was undertaken in 2018 and 2019.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec

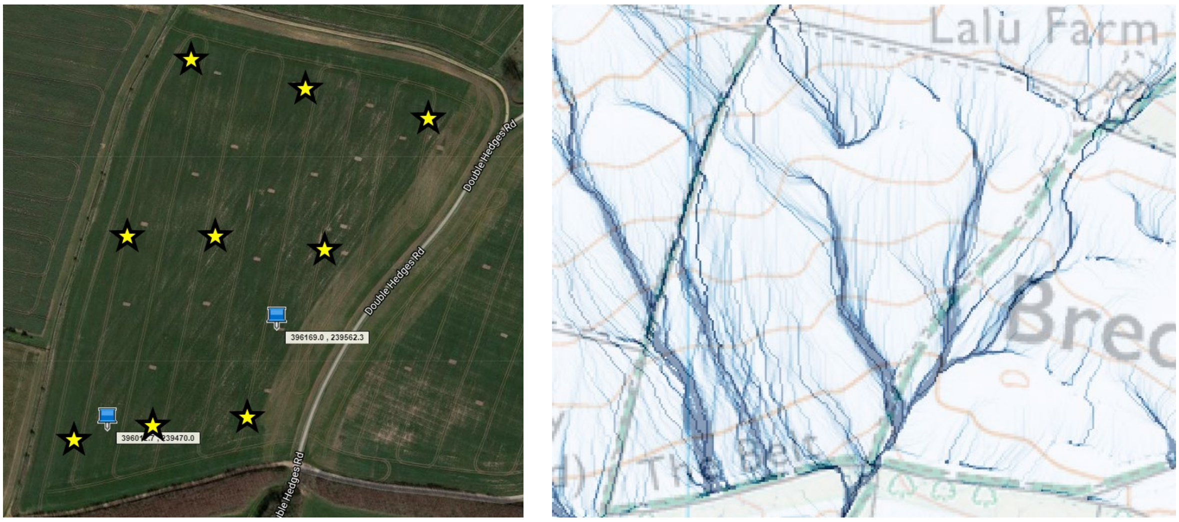
Soil sample analysis	Nitrate (NO_3^-)				x	x				x	x		
	Ammonia (NH_3)				x	x				x	x		
	Phosphate (PO_4^{3-})				x	x				x	x		
	Loss on ignition (SOM)				x	x				x	x		
	Bulk density			x					x				
	Soil moisture				x	x				x	x		
Water analysis/ assessments	Infiltration testing				x					x			
	Runoff sampling	(x)	(x)	(x)	(x)	(x)	(x)	(x)	Runoff traps out of the ground due to harvest			(x)	(x)
	Total Phosphorous (TP)			x		x							
	Phosphate (DRP)			x		x							

Table 4.3. Overview of field sampling and analysis undertaken during the PhD.

Assessments	Field sampling/analysis	Lab analysis	Statistical analysis
Soil	- Grain size distribution - Soil sampling (depth: 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm)	- Soil moisture - Loss on ignition (SOM) - Soil nutrients: Ammonia (NH_3),	- Nested ANOVA - One-way ANOVA - Tukey pairwise comparison

	- Bulk density (excavation method, depth: 0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm)	Nitrate (NO_3), Phosphate (PO_4^{3-})	- Pearson´s correlation test - Principle component analysis (PCA)
Water	- Water sampling (from agricultural streams) - Infiltration capacity (double ring infiltrometer) - Runoff traps	- Dissolved reactive phosphate (DRP) - Total Phosphorous (TP)	

Soil samples were collected from nine sampling locations per field (shown in Figure 4.3a) and from six points from the smaller CT field (see chapter 6 for more information) using a soil auger and collected in 10 cm intervals from 0 cm to 50 cm depth at each location. The soil samples were then brought back to the laboratory for analysis.



(a) (b)

Figure 4.3. (a) Ordnance Survey aerial photograph showing field NT-S with yellow marks representing soil sampling locations and blue marks showing the locations of the runoff traps and (b) topographic map with surface runoff calculations for field site NT-S.

The soil nutrients of Nitrate, Ammonia and Phosphate were measured as these are plant available forms of N and P with implications for both soil fertility and important contributors to water enrichment and contamination (Nitrate and Phosphate). This assessment explored the differences in distribution of the nutrients in the soil profile under different management practices to facilitate a discussion of the effect on the water purification function of the different soils. Soil Nitrate and Ammonia samples were prepped for analysis by weighing 5 g of air-dried sample and diluting with 50 ml of 2M KCl (potassium chloride) and shaken for 40 minutes on a rotary shaker to extract the nutrients from the soil sample. The samples were then filtered to remove nutrients and microbes and run through the Seal AA3 Autoanalyzer where concentrations of dissolved nutrients were determined by a digital colorimeter. The soil Phosphate was determined by the Olsen P extraction method that uses $NaCHO_3$ (pH 8.5) for nutrient extraction. The extraction solution (50 ml per sample) was mixed with 2.5 g of air-dried sample and shaken for 30 minutes on a rotary shaker. The samples were analysed manually by an acid colorimetric method with a colour spectrophotometer.

Phosphate and Total Phosphorous (TP) were also measured in water samples collected from watercourses downstream of the four study fields (Figure 4.4); these were analysed by the University of Exeter (as the University of Gloucestershire does not have the required facilities for the full analysis).

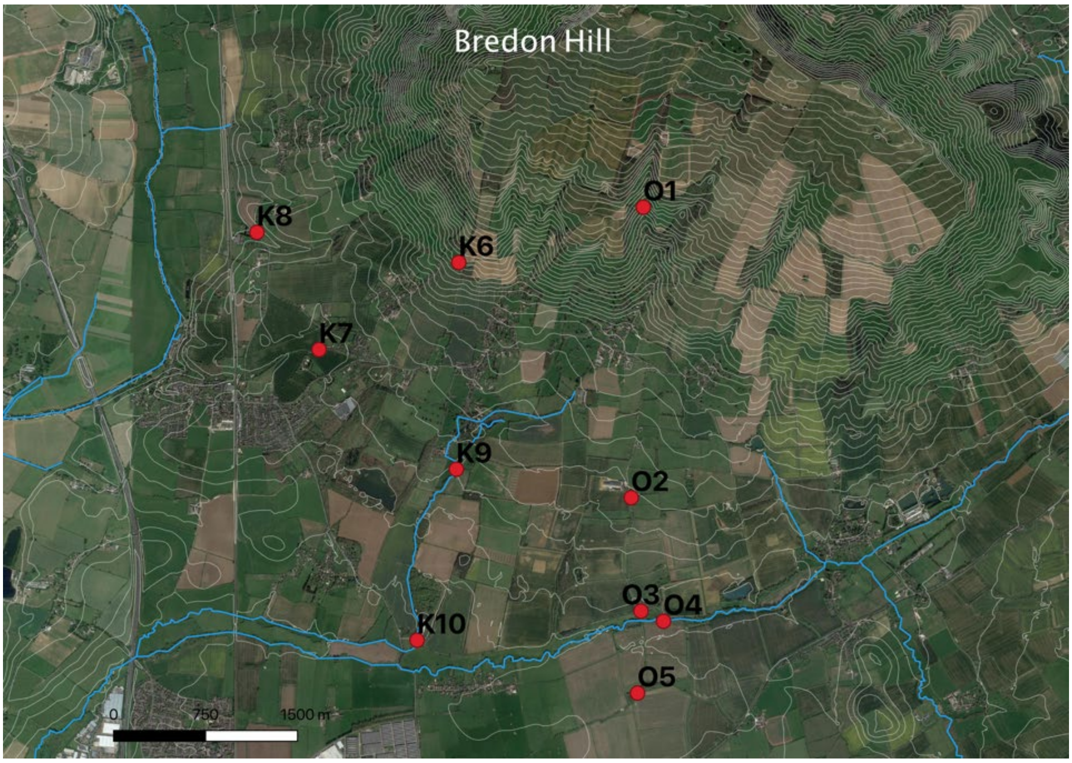


Figure 4.4. Water sampling locations across the two farms (O1-O5 relate to the NT fields and K6-K10 relate to CT fields).

Phosphate, also referred to as DRP (Dissolved Reactive Phosphate), is highly bioavailable and therefore an important variable when it comes to the contribution of agricultural runoff to eutrophication (Schoumans et al., 2014), while TP provides an estimation of the suspended solids content of the stream as P is normally bound to particles and the two variables are highly correlated.

Surface runoff was collected using eight custom-built runoff traps (Figure 4.5), with two traps positioned in each of the study fields (shown in Figure 4.3a). Their placement was based on surface flow calculations carried out in QGIS software using topography from a 5x5 m resolution Ordnance Survey Digital Elevation Model of the area downloaded from Edina Digimap, the traps were then positioned to capture maximum surface flow across the fields (an example is shown in Figure 4.3b).

Figure 4.5. Installation of runoff traps in the field.

The runoff traps consisted of a plastic sheet that was buried approximately 5cm into the ground that directed the surface runoff into a 2m long pipe (with drilled holes that the water could enter) that was sloping into a hose leading into water storage receptacle (shown in Figure 4.5). The water storage receptacles were inspected during soil sampling and after large rainfall events. The results from the runoff traps were omitted from the paper in Chapter 6 as there was exceptionally low rainfall over the two-year monitoring period and therefore there were nominal measurements of runoff made.

4.2.2.3 Statistical analysis

The statistical analysis was carried out by the Rstudio (version 1.1.463) software. The variance analysis was carried out by a one-way ANOVA and a nested ANOVA. The one-way ANOVA was used for variance analysis of the within-field values of the different variables, while the nested ANOVA provided a variance analysis of the different variables nested within the different fields within the farming practice (e.g. for differences in nutrient or SOM concentrations with sampling depth for each practice or soil type). A Tukey pairwise comparison analysis was carried out to compare values between fields, and a Tukey pairwise comparison test was used to determine the correlation between variables. The Principle Component Analysis (PCA) was carried out to calculate the variance and find the quality of representation of different variables.

4.2.2.4 Additional qualitative data collection

Additional qualitative data collection was carried out throughout the study, by interviews and conversations with the case study farmers and by attending relevant meetings. These interactions were informal and recorded mostly by keeping good field notes. Analysis was not carried out and the data were not included in the empirical chapters due to space limitations, and the focus of the papers. However, these discussions and observations provided insights which form the backdrop to the study and are used to support some points raised in the discussion (Chapter 9).

Table 4.4. Interviews and other supplementary activities.

Activity	Reason
Pre-study interviews with the case study farmers (March and September 2017)	Discussing soil and water monitoring, plot selection, and getting information about fields and field operations. Collecting farmers' experiences and perspectives on their tillage practices. Assessing their level of knowledge and learning about soil and water impacts.
Meeting representative from the Environment Agency (30 March 2017)	Discussing the study design, approaches to monitoring and options for monitoring water quality with SONDES.

LEAF workshop at Overbury (5 October 2017)	To observe and interact with farmers discussing Intercropping and to gain information about this and other practices
Interim meetings with the case study farmers	Informal meetings during the sampling period to discuss matters regarding sampling and field conditions/operations. Collect background information, details of field operations, move erosion traps etc..
Meeting representative from FWAG (18 April 2018)	Discussing the activities and farmer networks in the Carrant catchment in relation to farmer contacts and water quality sampling.
Natural England meeting (30 May 19)	Discussing the potential for NT as a 'nature-based solution' measure in relation to water retention and synergies between the projects.
Post-study meeting with the case study farmers (January 2020)	Discussion of results from the field monitoring with the case study farmers, to explain findings, and consult farmers to help interpret them.

4.2.3 Understanding farmer networks

This research contains two separate studies that aimed to contribute to our understanding about farmer learning and knowledge. These resulted in two different peer reviewed scientific articles. The first paper (Chapter 7) used a mixed-methods design with a SNA outlined in section 4.2.3.1 that incorporates a score-oriented quantitative approach with qualitative data collected concurrently through semi-structured interviews (section 4.2.3.2). The interviews were integrated into the analysis to supplement the SNA and strengthen the study by helping the interpretation of the patterns and complexity found in the SNA analysis (Chapter 7). The second paper (Chapter 8) used a combination of a Twitter content analysis of the EU project "SoilCare"and qualitative semi-structured farmer interviews with five farmers with an active profile on Twitter. The interview methods that were used in the Twitter paper are described in section 4.2.3.2, but the Twitter content analysis is not covered in this Methodology chapter as this work was carried out by the other authors, further details about the methods are provided in the methods section of the paper in Chapter 8.

4.2.3.1 Social network analysis

A SNA was undertaken to increase understanding of the dynamics of farmer networks and the nature and extent of farmer learning by addressing the objective: "to provide an analysis of NT farmers´ engagement with social networks, specifically in relation to the nature of information flow, knowledge exchange and learning between farmers, and identify the potential of farmer networks to enable this". A SNA is a body of research methods used to assess the structures of the connections among people with various social relationships, also known as social networks (Borgatti and Halgin, 2011, Wasserman and Faust, 1994) that includes network matrices, diagrams and mathematical measures (Bourne et al., 2017, Haythornthwaite, 1996). The data collection and analysis conducted in this study was carried out in accordance with standard methods. The SNA data was collected by the use of a SNA table (Appendix C) that was developed for this particular study collecting numerical and binary data to be entered in the online SNA Software Polinode (see Chapter 7 for a more detailed description of the SNA method).

4.2.3.2 Farmer interviews

Semi-structured in-depth interviews were conducted in both of the studies that were assessing farmer learning and knowledge (as additions to the SNA and Twitter analysis). A semi-structured interview is a common qualitative data collection method as it is both versatile and flexible, allowing the interviewer to improvise follow-up questions during the interview. The interview follows a determined set of questions that offers a structure for the discussion during the interviews, without restricting the interviewer to follow them strictly (Kallio et al., 2016) (see Appendix D and E for the interview guides that were used in the two studies). For both papers, the interview questions were derived from literature and aimed to build on existing evidence while addressing current knowledge gaps (full details of the interviewing methods are provided in Chapters 7 and 8). Interview transcripts were analysed using the qualitative analysis software NVivo (version 11.4.3).

For the 'SNA paper' (Chapter 7) the interviews were conducted to help the interpretation of the patterns and complexity found in the SNA analysis. The interviewees were all English farmers selected on the basis of their farm practice. The scope of the interviews was to evaluate farmers' engagement and ability to distribute information and share knowledge about NT through peer networks.

For the ‘Twitter paper’ (Chapter 8) the interviews were carried out with selected farmers with an active Twitter account to provide illustrative examples of Twitter usage. This improves understanding of farmers’ use of social media for supporting sustainable soil management. The questions aimed to address the reasons for using Twitter, the sort of knowledge exchanged, and the practical use of Twitter by these farmers.

This chapter has provided an overview of the methods that were used to collect, analyse and interpret the data presented in the four results chapters (Chapter 5-8). These chapters constitute the papers that make up the main body of this PhD-project presenting the results and discussing their meaning.

5 Paper I

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Review

The effect of no-till farming on the soil functions of water purification and retention in north-western Europe: A literature review

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ABSTRACT

This review provides a comprehensive evaluation of no-till (NT) based on recent studies (post-2000) in NW Europe and evaluates the separate effect of the NT and other associated practices (e.g. cover crops, crop residue and crop rotations) individually and collectively on the water purification and retention functions of the soil. It also assesses the applicability of NT compared to conventional tillage (CT) systems with reference to a number of soil physical characteristics and processes known to have an important influence on water purification and retention functions. The literature search was carried out by a systematic approach where NT practices were assessed against soil structure, erosion, nutrient leaching/loss, water retention, infiltration and hydraulic conductivity (combinations of criteria = 40). Articles were selected based on their relevance in relation to the topic and location within NW Europe (n = 174).

Results show that NT has large potential as an erosion mitigation measure in NW Europe with significant reductions of soil losses from agricultural fields, providing potential beneficial effects regarding inputs of sediment and particulate phosphorous (P) to water bodies. However, NT increased losses of dissolved reactive phosphorus (DRP) and had little effect on nitrogen (N) leaching, limiting the overall positive effects on water purification. Soil structural properties were often found to be poorer under NT than CT soils, resulting in decreased water infiltration rates and lower hydraulic conductivity. This was an effect of increased topsoil compaction, reduced porosity and high bulk density under NT, caused by the absence of topsoil inversion that breaks up compacted topsoil pans and enhances porosity under CT. However, several studies showed that soil structure under NT could be improved considerably by introducing cover crops, but root and canopy characteristics of the cover crop are crucial to the achieve the desired effect (e.g. thick rooted cover crops beneficial to soil structural remediation can cause negative effects in soils sensitive to erosion) and should be considered carefully before implementation. The contribution of NT practices to achieve Water Framework Directive (WFD) objectives in NW Europe is still uncertain, in particular in regards to water retention and flood mitigation, and more research is required on the total upscaled effects of NT practices on catchment or farm scale.

1. Introduction

Soil management is an important factor affecting the functionality of the soil. This paper draws on soil functions and ecosystem services concepts to review the effect of soil management on two water related functions; water purification and water retention. We define water purification according to the ecosystem services regulating concept of “filtering of nutrients”: if the solutes present in soil (e.g. nitrates, phosphates) are leached, they can become a contaminant in aquatic ecosystems (e.g. eutrophication) and a threat to human health (e.g. nitrate in drinking water). This is also defined by Schulte as one of five soil functions, where Nitrate (NO_3^-) and Phosphate (PO_4^{3-}) are the main elements of concern in relation to the quality of groundwater and surface water bodies, respectively (Schulte et al., 2006, 2014)[1]. Water retention is defined, according to the ecosystem services regulating concept of flood mitigation, as the capacity to store and retain quantities of water. This function can therefore lessen the impacts of extreme climatic events and limit flooding. Soil structure and more precisely

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macroporosity, as well as processes of infiltration will impact this service (Dominati et al., 2010). The water related soil functions of water purification and retention, are closely aligned to physical and chemical processes associated with the movement of water through soils (Svanbäck et al., 2014). A number of soil properties and processes influence these soil functions, and these in turn are dependent on a range of variables, such as soil type, climate and, most significantly, farming practices; however, there is no consensus that practices that benefit one soil function benefit them all (Soane et al., 2012; Frank et al., 2014).

Agricultural systems are responsible for nutrient and sediment losses into waterways, representing a challenge both in regards to the threat of soil losses from agricultural fields, and polluting water resources (Young et al., 1989; Carpenter et al., 1998; Vogel et al., 2016). Soil surface infiltration of water is a function of pore size distribution and the continuity of pores and flow paths (Ehlers, 1975; Lipiec et al., 2006). During heavy precipitation events excess water, not able to infiltrate into the ground due to high soil saturation or low hydraulic conductivity, runs on the soil surface as runoff (Smith et al., 1993; Buczko et al., 2003). This surface water is likely to carry nutrients and sediments that can cause diffuse pollution to receiving water bodies, as well as flooding. Additionally, nutrient leaching through subsurface flows, is an important source of pollution from soils containing large amounts of water soluble nutrients (Hansen et al., 2000; Schoumans et al., 2014; Taylor et al., 2016). The challenge of soil and water management, and conflicting interests between intensive farming and the need to protect nearby aquatic systems, has been an important incentive for the creation of water conserving strategies and frameworks, notably the Water Framework Directive (WFD). The WFD is an EU regulation for integrated river basin management for Europe that has been implemented to help improve and protect the ecological health of rivers, lakes, estuaries and coastal and groundwater. The aim of the framework is that all water bodies should achieve at least 'good ecological status' by 2027 (according to the WFD classification system), on the basis of criteria and boundaries defined against biological, physicochemical and hydromorphological elements (European Commission, 2015).

In conventional farming systems (CT), the soil is normally cultivated by a mouldboard plough that inverts the top layer (around 20 cm) of the soil to loosen it and create a suitable seed bed (Townsend et al., 2015). When the soil is ploughed, hard surface pans and topsoil compaction is loosened. This process allows a higher degree of oxidation and mineralisation of the organic matter, which is beneficial for plant growth as more nutrients are transformed to plant available forms. Nevertheless, in the long-term the enhanced chemical activity may harm the soil as soil organic matter (SOM) is mineralised at a much higher rate than under low disturbance systems (Balesdent et al., 2000). SOM is essential for soil structure and key for all soil functions (e.g. Balesdent et al., 2000; Doran and Zeiss, 2000). In addition, a ploughed soil surface without protective crop residue or other plant cover makes the soil vulnerable to erosion, and is therefore a likely source of diffuse agricultural pollution (Lundekvam, 2007; Vogel et al., 2016).

No-till farming (NT) can potentially mitigate some of these effects. NT, also referred to as "zero tillage", "direct drilling" and occasionally as "conservation tillage" has been widely implemented by farmers globally. The definition of conservation tillage varies significantly in the literature and is often used as a generic term describing less intensive tillage systems like NT, minimum tillage and reduced tillage, often in combination with at least 30% residue cover. NT is defined as a cultivation method without soil inversion, where the seeds are drilled directly into the ground (Townsend et al., 2016). Minimal soil disturbance by the absence of ploughing or harrowing is intended to promote good soil structure and better habitat for beneficial soil biodiversity (Bertrand et al., 2015; Crotty et al., 2016). NT was first developed in Central and South America as a soil water conserving measure, but has also been adapted by farmers elsewhere in order to increase the SOM content of the soil and to reduce fuel and labour costs by reducing the time needed for field operations (Lahmar, 2010; Kassam et al., 2012). NT systems can, it is argued, reduce nutrient and sediment losses to downstream waters by decreasing runoff from agricultural fields (Schoumans et al., 2014; Mhazo et al., 2016) and therefore potentially contribute to achieving objectives set by the WFD, in addition to acting as a soil improvement practice.

NT farming is often associated with other crop and soil management practices, such as growing cover crops, maintaining soil cover using crop residues, and crop rotations; when applied together these are often referred to as Conservation Agriculture, where minimum soil disturbance, permanent soil cover and crop diversity are core principles (Lahmar, 2010). These practices underpin the beneficial, as well as reduce the less beneficial, effects of non-inversion tillage. Providing soil cover by cover crops and crop residue potentially protects the soil from runoff by slowing down the water flow, enhancing infiltration, and reducing erosion risk by binding the topsoil with crop roots (Döring et al., 2005; De Baets et al., 2011). Additionally, crop residue is beneficial to earthworms and other organisms in soil that contribute in adding SOM back to the soil. Increased crop diversity, both by cover crops and crop rotations helps soil accommodate higher biodiversity of beneficial invertebrates and microorganisms (Crotty et al., 2016). This is also an important method to suppress weeds, which can be a challenge in non-inversion systems (Soane et al., 2012).

The aim of this review is to investigate results from recent studies of NT practices carried out in NW Europe and assess how they are affecting the water purification and retention functions of the soil. There have been a large number of studies focused on NT practices from other parts of the world, but these are not always transferable to Europe. In particular, many focus on water conserving impacts of NT whereas in NW Europe's context, with its primarily Oceanic climate (Peel et al., 2007)[2], excess water is often a problem (Soane et al., 2012). There is a demand for an overview of NW European findings so that management recommendations are based on relevant research evidence. Specifically this is an important step towards more efficient and targeted farming practices, to benefit both the farmer and the environmental management. Previous reviews tend to focus on impacts of NT on soil in relation to crop production rather than other soil functions (e.g. Busari et al., 2015), we have chosen to conduct the review from the perspective of water purification and retention functions which provides the main structure for the paper. In order to decide whether NT should be recommended as a system which can contribute to achieving water management objectives in NW Europe set by the WFD, a compilation of recent research findings is needed.

Objectives:

- Provide a comprehensive evaluation of NT based on recent studies (post-2000) in NW Europe and evaluate the separate effect of the NT and other associated practices (e.g. cover crops, crop residue and crop rotations) individually and collectively on the water purification and retention functions of the soil.
- Assess the applicability of NT compared to CT systems with reference to a number of soil characteristics and processes associated with water purification and retention functions.

2. Methods

2.1. Selection criteria and boundaries

This review assesses the results from recent studies (after the year 2000) carried out in NW Europe (here defined as Ireland, the UK, Germany, the Netherlands, Belgium, Denmark, Norway, Sweden, Iceland, Northern France, Switzerland, Austria and Luxembourg) that research the potential of NT management to reduce soil loss and

[2] According to the Köpping climate classification.

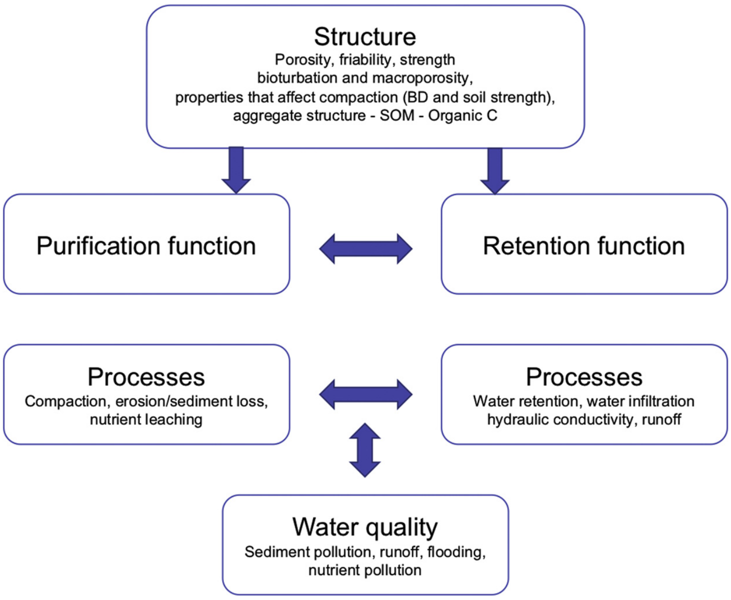

Fig. 1. The framework of the review; the effect of soil structural properties on soil water functions and processes influencing water quality.

nutrient input to waterbodies (as a means to achieve the objectives set by the WFD). NT and the associated crop and soil management practices are assessed separately against soil structure, erosion, nutrient leaching/loss, water holding capacity, infiltration and hydraulic conductivity to assess the impact on the water purification and retention functions (see Supplementary material). These were selected because of their known significance in purification and retention functions (see Section 1). These structural properties and processes provide the framework for the review, however in practice they are significantly interlinked (Fig. 1).

In presenting the results, inevitably, where processes and functions are interrelated, and where papers report on a number of variables and outcomes, there will be some repetition and the same paper will be used to provide evidence under a different heading. We have tried to avoid this where possible or make reference to another section in the paper to save repetition.

Cover crops, rotations and soil cover by crop residues were both viewed together with NT and separately to assess the potential of these practices to mitigate the negative effects and enhance the benefits of NT. It is important to assess the potential of, for example, different species of cover crops as these are often integral to NT farming systems; and a lot can be learned from separate research in cover crop impacts.

The literature search was primarily carried out in the ISI Web of Knowledge database, combined with Science Direct. The database was selected due to the comprehensive content of journals and articles relevant to the subject. A search was carried out for each of the combinations of criteria (n = 40), and articles selected based on their relevance in relation to the topic location within NW Europe (n = 174).

3. Soil structural properties

Soil structure is an important indicator of soil quality in that it impacts the chemical, physical and biological processes of the soil (e.g. Munkholm et al., 2003; Bronick and Lal, 2005; Piron et al., 2017), and has an important influence on the soil functions of water purification and retention (Fig. 2). A number of soil physical properties are associated with soil structure: porosity, aggregate structure and stability, friability, strength and bulk density. High total and air-filled porosity and infiltration rate are associated with good soil structure, while high bulk density values indicate poorer structure (Mueller et al., 2009).

Soil management, the method of tillage in particular, is crucial for soil structure, and practices that do not invert the soil are often seen to benefit the soil through improved structure (Kassam et al., 2014). Abdollahi et al. (2014) who assessed the effect of different tillage systems in combination with cover crops in a long-term field trial on sandy loam in Denmark, found smallest mean weight diameter, and therefore the best soil friability under CT compared to NT management and harrowing. However, they also discovered that soil friability and quality under NT could benefit from establishing cover crops (fodder radish (*Raphanus sativus* L.)) as the cover crop treatment reduced the penetration resistance of the soil. Rücknagel et al. (2016), on the other hand, investigated the effect of cover crops on topsoil structure on five one year trials in Germany (sandy loam/silty clay loam/silt loam), and found that the soil structure only rarely benefited from cover crop cultivation. The two studies used different species of cover crops, and less beneficial effect of blue lupins (*Lupinus angustifolius* L.), field beans (*Vicia faba* L.), field peas (*Pisum sativum L. con-* var. *speciosum (Dierb.*) and vetch (*Vicia sativa* L.) used by Rücknagel et al. (2016) compared with fodder radish used in Denmark, could be a possible reason for the conflicting results. This idea is supported by Burr-Hersey et al. (2017) who found that tillage radish and black oats (*Avena strigosa*) were more suited for soil structural remediation than vetch.

There seems to be a consensus that crop rotations generally improve soil structure (Schjønning et al., 2002; Askari et al., 2013; Gotze et al., 2016), especially in the topsoil (Gotze et al., 2016; Jarvis et al., 2017). Although, the type of crop rotation that is implemented in a field can influence soil structure. Gotze et al. (2016) found that different rotation combinations had varying impact on structural properties such as soil compaction risk and hydraulic conductivity.

4. Water purification function

4.1. Soil stability

4.1.1. Aggregate structure and organic carbon

Aggregate structure and stability are important soil structure variables, impacting the general soil structure and its resistance to erosion and compaction. Higher structural stability and more consistent water

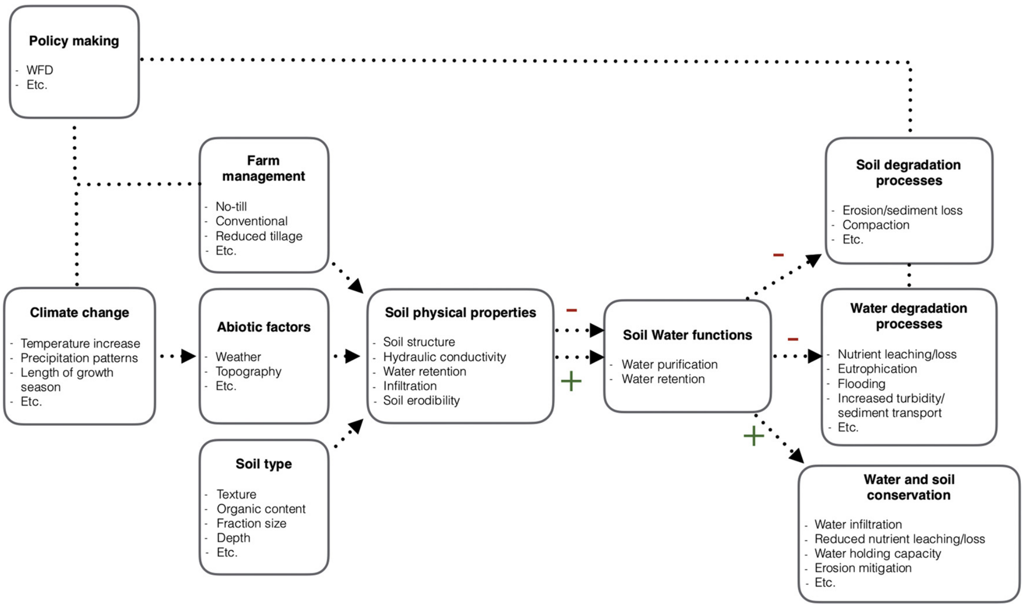

Fig. 2. Overview of the effects of soil physical properties on the water purification and retention functions of the soil. The red minus signs represent degradation (i.e. diminished capacity to provide functions) and the green crosses conservation.

distribution in the soil due to uniform aggregate strength and bulk density in aggregates under NT was found by Urbanek et al. (2014) on a silty loam soil field site in Germany. This was confirmed by Moncada et al. (2014) who found that aggregates from a sandy loam and a silty loam soil in a NT system in Belgium were more resistant to break down after wet sieving, and Abdollahi et al. (2014) who showed that NT and harrowing resulted in better soil strength on sandy loam in Demark in terms of greater mean weight diameter, visual evaluation of soil structure, water stable aggregates, aggregate tensile strength and rupture energy than under CT. Microbial activity is stimulated by higher levels of organic matter, as often seen in NT top soils, and this leads to the formation of bonding and binding agents in the soil (Elmholt et al., 2008). The addition of plant matter to the soil as a result of mulching therefore has the potential to contribute to higher topsoil aggregate stability (Frøseth et al., 2014).

The organic carbon (C) content of the soil has been shown to affect aggregation (Moncada et al., 2014; Kainiemi et al., 2015) and is often distributed differently in the soil profile under NT and CT; with NT often resulting in an evident stratification of C, with higher concentrations in the topsoil layer (Oorts et al., 2006; Hazarika et al., 2009). This was confirmed by Ulrich et al. (2006) who assessed the effect of different tillage systems on soil quality on a sandy loam in Germany and discovered a 9% increase in organic C in the NT system compared to CT.

4.1.2. *Erosion/soil loss*

A number of studies have shown that NT has decreased surface runoff (Leys et al., 2007; Hösl and Strauss, 2016), erosion risk and soil loss in NW Europe (Gaiser et al., 2008; Todorovic et al., 2014; Vogel et al., 2016) (Table 1). The beneficial effects are closely related to enhanced surface protection associated with this type of system provided by crop residues and vegetation (Armand et al., 2009; Todorovic et al., 2014). Reduced soil disturbance under NT largely affects soil stability and therefore the resistance to erosion (Knapen et al., 2007; Routschek et al., 2014; Nano et al., 2015).

In a study into the effect of different cropping systems on soil erosion, Lundekvam (2007) found that practicing NT in the autumn could reduce soil losses by up to 90% on Norwegian clay soils. Tillage in the autumn exposed bare soil to a large amount of surface runoff in the CT system, while plant and residue cover under NT protected the soil surface. Similar numbers were predicted by a German study by Vogel et al. (2016) using a soil erosion model based on a field site in Brandenburg. Changing practice from CT to NT was the erosion mitigation measure with the highest potential in their study, with 90–100% reduction in soil losses, based on three rainfall events with recurrence intervals of 2, 20 and 100 years.

Higher topsoil bulk density, as often seen in topsoils under NT, can be beneficial to erosion mitigation by decreasing soil detachment caused by concentrated flow (Knapen et al., 2008a,b; Van Gaelen et al., 2014). For this reason Knapen et al. (2008a) proposed compacted zones of concentrated flow, in combination with NT or grassed waterways, as a potential measure to combat soil loss. Although, tramlines established by farm machinery may already serve this purpose. In a study carried out in the UK where in-field mitigation options for sediment and Phosphorous (P) loss were assessed, Deasy et al. (2009) found that tramlines had a dominant role in transporting runoff, sediment and P. Reduction of compaction in the tramlines seemed to be the measure with the highest potential for erosion mitigation, in contrast to the findings of Knapen et al. (2008a).

In CT systems, the highest erodibility occurs shortly after tillage, when the vegetation cover is at its lowest (Knapen et al., 2007; Lundekvam, 2007). Canopy coverage and rooting density strongly affect soil structure and erosion rates (Bodner et al., 2010), but the ability of cover crops to reduce runoff largely depends on crop type and the time of the year (Martin et al., 2010; De Baets et al., 2011). In a study on the erosion reducing effect of different cover crop roots on a Belgian Loess soil, De Baets et al. (2011) found that cover crops with thick roots (e.g. white mustard (*Sinapis alba*) and fodder radish) were less efficient in reducing soil loss by concentrated flow than ones with more fine-branched roots (e.g. ryegrass (*Lolium multiflorum*) and rye (*Secale cereale*)). They concluded that considering both above and below ground plant characteristics, ryegrass, rye oats and white mustard were most suitable to prevent concentrated flow erosion. These findings indicate that cover crop species suitable for erosion mitigation have different root properties than species suitable for loosening compaction (cf. Section 3: findings by Abdollahi et al. (2014) and Burr-Hersey et al.

Table 1
Erosion/sediment loss rates from different NW European study sites comparing CT with NT systems.

	Country	Soil type	Annual precipitation	Mean temperature (°C)	Erosion rate	Type of data
Frank et al. (2014)	Germany	Loamy/sandy soil	800–900 mm	6.5–7.5	87,7% reduction per year under NT	Modelled data, GISCAME (based on the Universal Soil Loss Equation)
Hösl and Strauss (2016)	Austria	Gleysols, Regosols, Cambisols and Planosols[a]	950 mm^{-1}	8.3	71.4% reduction per rainfall event (return probability of about 20 years) under NT	Rainfall simulation, experimental fields
Leys et al. (2007)	Belgium	Silty loam	800 mm	9.7	Reduction in 88% of the cases under NT during extreme natural rainfall simulations	Rainfall simulation, small scale plots
Lundekvam (2007)	Norway	Silt clay loam	785 mm	5.3	Up to 90 % reduction per year under NT	Modelled data, USLE and RUSLE
Routschek et al. (2014)	Germany	Silty soil	607 mm	7.8	91% reduction under NT (simulated for future time period from 2031 to 2050)	Modelled future scenarios, Erosion-3D
Ulén and Kalisky (2005)	Sweden	Silty soil	634 mm	4.9	83.2% reduction per year under NT	Plot experiment
Vogel et al. (2016)	Germany	Regosols, Luvisols and Gleysols[a]	463 mm	7.8–9.5	90-100% reduction under NT during rainfall events (2, 20, 100 years return probability)	Modelled data, Erosion-3D

[a] Classified according to the WRB (IUSS, 2006).

(2017)). Additionally, several studies show that soil cover by crop residues has a positive effect on surface runoff and soil erosion mitigation (Döring et al., 2005; Deasy et al., 2009; Morris et al., 2010; Bailey et al., 2013; Van Gaelen et al., 2014). The number of crops per rotation (Koschke et al., 2013), the type of crops, and the carry-over effects from one crop to the other affect erosion rates as well (Prasuhn, 2012; Fiener and Auerswald, 2014).

4.2. *Nutrient leaching*

Nitrogen (N) and P are two of the primary nutrients important to crop growth and development. Although they occur naturally in the soil, additional nutrients are added to agricultural fields by organic or synthetic (artificially manufactured) fertilisers for enhanced growth. As N and P are normally limiting nutrients in aquatic systems (Smith, 1983; Dodds and Smith, 2016), runoff and leaching from arable fields represents a pronounced environmental threat. This diffuse pollution from arable fields causes water quality degradation that may lead to nutrient enrichment of water bodies (eutrophication) and algal blooms (Carpenter et al., 1998; Hilton et al., 2006; Cooper et al., 2017).

Loss of soil P occurs in both particulate (PP) forms, where P is absorbed onto mineral surfaces, and as dissolved reactive forms (DRP) (Daniel et al., 1994; Svanbäck et al., 2014); inorganic forms of P are available to plant roots, while dissolved organic forms (DOP) need to be mineralised by microbes to become plant available. DRP is highly reactive and the form can leach from soils through vertical water movement (Daniel et al., 1994) and reach surface waters by tile drainage (Ulén et al., 2010) or surface runoff. In this review loss of particle bound P (PP) by erosion was found to be lower in NT systems than under CT (Ulén and Kalisky, 2005; Schoumans et al., 2014), but DRP losses show a different pattern with higher losses under NT (Ulén and Kalisky, 2005; Ulén et al., 2010; Schoumans et al., 2014). A study by Ulén and Kalisky (2005), which aimed to outline measures to reduce erosion and P losses from a silty soil to improve water quality in a Swedish lake, found that implementing NT could reduce the suspended solids (SS) load by 83% and PP by 56%. However, the loss of DRP increased by 75%. These findings were underpinned by a Scandinavian review by Ulén et al. (2010) that evaluated the effects of various soil tillage practices on losses of PP and DRP via surface runoff and tile drainage, and concluded that NT poses a higher risk of DRP loss, whilst also offering great potential in reducing PP losses and water erosion from unstable, erodible clay loams and clay soils. Increased losses of DRP under NT systems can be explained by increased enrichment of nutrients in the topsoil (Taylor et al., 2016) and leaching from the plant material that is normally left on the soil surface under NT, which release P that accumulates in the topsoil (Ulén et al., 2010). Further, dead or frost damaged vegetation is known to be an important source of DRP (Ulén and Kalisky, 2005)

N leaching is likely to occur when the soil contains a large amount of soluble inorganic N and weather conditions contribute to percolation from the root zone. NO_3^- is the water soluble form of N that is a result of nitrification of ammonium (NH_4^+) (Hansen et al., 2000), often supplied by the application of fertiliser (Hansen et al., 2015). Both forms are plant available, but as the ammonium is positively charged it attaches to negatively charged soil and organic matter, and does therefore not leach to the same extent as NO_3^-. Total N levels refer to the sum of NO_3^-, ammonia (NH_3) and, nitrite (NO_2) and organic N compounds.

Although high spatial variability can be expected with nutrient leaching, due to different soil properties and soil moisture, e.g. affecting the rate of local-scale subsurface transport (Kistner et al., 2013; Svanbäck et al., 2014), several studies found that the NT does not reduce nutrient leaching compared to CT (Oorts et al., 2007; Svanbäck et al., 2014; Hansen et al., 2015; Cooper et al., 2017). For example in a long–term study at two experimental sites in Boigneville (France), Oorts et al. (2007) assessed mineral N dynamics in a Haplic Luvisol (loess parent material). They found no significant differences in N mineralisation and leaching between NT and CT sites, but discovered different distributions of N within the soil profile, with significantly higher NO_3^- content in the upper soil layer under NT. This was also demonstrated by Cooper et al. (2017) who assessed the efficiency of cover crops and non-inversion tillage regimes at minimising farm scale nutrient losses on a clay loam/sandy clay loam in the UK. They found no separate positive effect of NT, but when combined with a winter oilseed radish cover crop NT or shallow non-inversion tillage decreased N leaching by 75–97%, relative to winter fallow with mouldboard ploughing.

In contrast, another long-term experiment in France investigated the effect of different agricultural practices on N balance (Constantin et al. 2010) and found that N leaching was reduced under NT, but similarly to Cooper et al. (2017) argued that the practice should be combined with cover crops (also called catch crops, i.e. they catch the N) to become more efficient due to a higher N uptake (both by the main crops and the cover crop). In a Soil and Water Assessment Tool analysis Taylor et al. (2016) found that introducing red clover to a UK catchment could decrease total P losses by 1.6%. The reduction in N losses were much higher (19.6%), as the potential for cover crops to reduce P losses is limited due to the slow desorption of P from soil particles. This was supported by Cooper et al. (2017) who did not discover any impact of cover crops on P losses.

The choice of rotation or cover crop species also influences nutrient leaching, shown by a literature review assessing the ability of cover crops to reduce N and P losses from arable land in Scandinavia and Finland by Aronsson et al. (2016) who found that red clover (*Trifolium pratense*) (legumes species, fixating N to plant available forms) cover crops on clay soil increased the N leaching by 62%, while perennial rye grass (*Lolium perenne*) cover crops on sandy soil reduced N leaching by 85 to 89%. The same was evident for P loss, with a respective increase of 86% and reduction of 43%.

5. Water retention function

The soil-water relationship is one of the most important physical phenomena affecting the water retention function of the soil, and is significantly influenced by soil management practices (Fig. 2) (Strudley et al., 2008). Two of the most important soil hydraulic properties are soil water holding capacity, often expressed as the soil water retention curve, and hydraulic conductivity (Cornelis et al., 2005). These variables are key elements in determining water movement in soils, and its accessibility to plants (Horel et al., 2015). The rate at which water infiltrates and moves through the soil is largely dependent on soil structural properties, such as porosity (Buczko et al., 2003; Mueller et al., 2009), the soil saturation level and the water holding capacity of the soil. These variables all contribute to runoff generation, however there is limited published evidence from NW Europe regarding the potential of NT systems to regulate water and therefore contribute to flood mitigation.

5.1. Water holding capacity

The water holding capacity, or soil water retention, describes the relationship between the soil's matric potential (the difference between pore air pressures and pore water pressure), and its water content (Cornelis et al., 2005; Liu et al., 2012). There is no real consensus in the literature as to whether altered soil properties under NT enable higher retention of water. Chirinda et al. (2010) assessed differences in soil properties under different management strategies on a sandy loam in Denmark and found higher soil water retention and volumetric water contents in NT soils. Abdollahi et al. (2014) found the opposite in their study into the effect of three tillage treatments and cover crops on soil pore characteristics on a sandy loam in Denmark. In a French study on silty clay loam soil, Nano et al. (2016) showed that the NT system had low retention values close to saturation (due to preservation of soil structure due to the absence of soil inversion) and high values at the dry-end of the water retention curve (due to more favourable soil physical and chemical properties under NT, such as higher clay and organic carbon contents).

The total soil porosity, which influences the water holding capacity, is often found to be greater in soils of CT than in NT (Abdollahi et al., 2014; Schwen et al., 2015), but these studies are only considering the topsoil, above the plough layer. In a study carried out on silty and sandy loam soils is Germany, Hangen et al. (2002) found that silty soils with less disturbance had much deeper percolation, probably due to more favourable conditions for burrowing soil animals providing deep vertical macropores. Enhanced porosity by a higher abundance of continuous macropores can be achieved by the application of cover crops (see Section 5.2.1), however, other hydrological parameters did not show the same significant effect of the soil cover treatment.

5.2. Water infiltration

Infiltration rates largely depends on soil type/texture and soil structural properties, but is also affected by other variables, such as cracking and swelling of soils with different weather conditions (Lundekvam, 2007; Svanbäck et al., 2014) and/or soil compaction creating soil crusts of very low permeability (see Section 5.2.2) (Rücknagel et al., 2017). In a study of the impact of tillage, rotation and traffic on topsoil structure Mueller et al. (2009) found lower infiltration rates, poorer structure and higher bulk density in the topsoil under NT than CT on loamy sand at a German field site. Similar observations were found in another German study by Buczko et al. (2003), where infiltration and macroporosity in two contrasting tillage systems were compared. Results showed that CT provided a higher infiltration rate at saturation in the silt loam soil, but the opposite was the case for infiltration below 30 cm (down to 1.2 m). The two studies confirm that degradation of topsoil structure is a challenge in NT systems, but the results from Buczko et al. (2003) show that the infiltration rate varies largely through the soil profile. In their tracer experiment they also found that the penetration depth under CT was only 0.5 m, while it was 1.2 m under NT.

With regards to cover crops, a study in Austria by Bodner et al. (2008) aimed to identify key factors underlying hydraulic conductivity dynamics found that pore clogging by cover crop roots with intense growth (phacelia (*Phacelia tanacetifolia*) and vetch) was documented in a silt loam. They suggested that cover crop ability to influence infiltration rates is largely governed by natural temporal variability of structure-related hydraulic properties in the field. The type of crops included in a rotation as well as the type of rotation practiced are likely to affect infiltration rates as well, and Gotze et al. (2016) found better structural stability and infiltration capacity in a field with crop rotations than in a monoculture field.

5.2.1. Bioturbation and macroporosity

Bioturbation is an example of 'ecosystem engineering' where soil organisms, including microbes, rooting plants and burrowing animals, are reworking the soil and sediments (Meysman et al., 2006). The biological activity is essential for creating macropores - large continuous openings in the soil (often with diameter > 30 μm) representing an important structural property (Lipiec and Hatano, 2003; Czachor and Lipiec, 2004). Non-inversion tillage systems that disturb the soil less are often associated with a higher abundance of earthworms, with a beneficial effect on soil structural properties. Recent studies comparing earthworm populations at field sites under different management practices, however, present slightly conflicting results. In a study of pore morphological changes due to mechanical and biological processes in the surface layers of a silty soil in France, Hubert et al. (2007) found the total macroporosity of the soil to be two to five times lower under NT than under CT, limiting earthworm activity. The decrease in macropores was measured after four years of NT management, which indicates that these structural changes occurred over time. Similarly, a study of tillage effects on structural quality in the topsoil of a sandy loamy soil in Denmark carried out by Garbout et al. (2013) and research on sandy loams /silty soils (Peigné et al., 2009, 2013) showed a generally higher number of pore networks, branches and junctions under CT due to greater compaction under NT. The NT soil did however have a dominance of vertical macropores, which indicates the presence of anecic (vertically burrowing) earthworms (Peigné et al., 2009) that could potentially enhance the soil's ability to drain and transmit water (the hydraulic conductivity), affecting the infiltration rates of the soil. In contrast, a French study, by Piron et al. (2017), detected higher occurrence of bioturbation due to earthworm activity under NT than under CT on a loamy sandy clay and a silty loam by using a visual soil structure method.

The combination of NT with cover crops has been shown to benefit earthworm populations (Peigné et al., 2009) and improve soil macroporosity (Bodner et al., 2013; Abdollahi et al., 2014). In addition to potentially creating a better habitat for earthworms, cover crops positively influence water and gas transport and create better growing conditions for other crops. Retaining crop residue rather than removing it from the field provides more organic material to the soil surface and may therefore increase both earthworm and biomass densities (Frøseth et al., 2014). Earthworm populations and the occurrence of biopores are also influenced by soil type (Piron et al., 2017) and the type of crop rotation a field is under (Kautz et al., 2014; Capowiez et al., 2009; Jarvis et al., 2017) found that long-term inclusion of grass-clover leys on a silt loam in Sweden resulted in increased populations of epigeic (small, litter feeding earthworms on the surface or first few cm of the soil) and endogeic (medium-sized, soil-eating earthworms influencing the regeneration of soil aggregates) earthworms. It has been argued that the addition of mulch may result in better living conditions for earthworms, and therefore increased macroporosity (Pelosi et al., 2017), however others have found that extensive mulch residues prevented water transport beneath 5 cm soil depth in a low intensity podzolluvisol system (Hangen et al., 2002) thus impacting the infiltration rate.

5.2.2. Properties that affect compaction

Topsoil compaction is often highlighted as one of the main challenges to NT systems, with the potential to significantly reduce infiltration rates, whereas in CT systems loosening of compacted topsoil layers is achieved by mouldboard ploughing. The absence of soil inversion in NT systems can create compacted clods (Peigné et al., 2009, 2013), also known as "NT pans". The work of Munkholm et al. (2003), where temporal and spatial effects of two different direct drilling techniques were assessed on a sandy loam in Denmark, supports this view, and found critically high penetration resistance and bulk density in their NT field. The soil susceptibility to compaction is highly dependent on soil texture, climatic conditions, management decisions (e.g. timing of field operations in relation to soil moisture content), and other soil properties, affecting the suitability of NT. In a study on the effect of farming practices on bulk density and mechanical resistance on a silty soil in Denmark, Chaplain et al. (2011) found that one of the NT sites had higher mechanical resistance to compaction due to increased precompaction stress values when close to saturation, and decreased impact of wetting/drying cycles on soil structure (Table 2). Similarly, although only assessing the lower topsoil, Rücknagel et al. (2017) found higher stability against mechanical loads in NT soil when assessing seven different study sites of sandy clay soils in Germany, and argued that restoring sufficient macropore volume should be possible in already compacted NT soils.

Reduction in compaction by planting cover crops has been found to have a positive effect on soil structural remediation in compacted layers (Abdollahi et al., 2014; Burr-Hersey et al., 2017), and may therefore represent an important practice in NT systems. The success of this treatment varies largely with the nature of the root system (cf. Section 3: findings by Burr-Hersey et al. (2017)). However, for cover crops to have a favourable impact on soil structure, it is crucial to make sure that the increase in field operations needed to cultivate them does not cause any new compaction (Rücknagel et al., 2016).

5.3. Hydraulic conductivity

Hydraulic conductivity is a function of the soil-water content or potential (Green et al., 2003), that describes the movement of water through soil pores and fractions. Conflicting results regarding the effect of NT on hydraulic conductivity have been found (Table 3). The absence of tillage has the potential to enhance the hydraulic conductivity of the soil (Kechavarzi et al., 2009; Schwen et al., 2011b; Nano et al., 2015; Pelosi et al., 2017), potentially making soils more resistant to runoff and erosion during heavy precipitation events. However, several other studies detected lower hydraulic conductivity in NT than under CT (Ulrich et al., 2006; Schwen et al., 2011b; Crittenden et al., 2015). One potential explanation to these contradictory results is that there is greater variability in hydraulic conductivity between soil types, that can exceed the variety between different land use systems (Bodner et al., 2007).

Cover crops with high rooting density and coarse root axes (e.g. some legume species) have been shown to enhance hydraulic conductivity in the saturated and near-saturated range. In a study assessing the effect of different management practices on hydraulic conductivity and crop yield on a marine clay loam in the Netherlands, Crittenden et al. (2015) found both spatial and temporal variability, with variations in the saturated hydraulic conductivity throughout the year, but a higher consistency in the autumn than in the spring. Several studies are based on observations made in the spring, and some are only based on one sampling date, this may give an oversimplified and incorrect picture of the differences in hydraulic conductivity between farming systems. Hydraulic properties are dynamic and varying largely with climatic conditions such as soil drying, frost and rainfall events, and management induced changes should therefore be assessed considering both spatial and temporal variations (Bodner et al., 2008).

6. Discussion

In reviewing the literature, it is evident that NT has varying effects on the water purification and retention functions of soil, and results from NW European studies are often conflicting and lack consensus. This is in part due to the differing local trial conditions, furthermore NT is not a prescriptive system, it is operationalised differently by different farmers and trialists. This highlights the complexity of the system and the difficulties in identifying any general relationships. Sampling methods, depth, and the time of the year of sample collection can largely influence the results. Furthermore, fewer studies that have been conducted in NW Europe than in other parts of the world, providing less evidence to allow consensus to emerge. It is also clear that there is a suite of interrelated soil structural properties that affect the purification and retention functions and associated processes (Fig. 2). As such collating and synthesising the evidence available concerning the impact of NT is challenging.

Soil pore structure, an important soil quality variable influencing chemical, physical and biological processes, was often found to be in a poorer state under NT practices than under CT (Garbout et al., 2013; Peigné et al., 2013; Abdollahi et al., 2014; Moncada et al., 2014; Rücknagel et al., 2017). The earthworm occurrence and macroporosity, caused by bioturbation in NT systems compared with CT, differed between studies, but the anecic species that are drilling deep vertical burrows were more abundant in NT systems (Peigné et al., 2009; Garbout et al., 2013), potentially affecting infiltration and water storage in deeper layers of the soil (Buczko et al., 2003). Nevertheless, macropores can also pose a risk by increasing preferential flow, that can lead to nutrients leaching to the groundwater or to surface waters by

Table 2
Bulk density from different NW European study sites comparing CT with NT systems (the values are based on the average of all observations from each of the studies).

	Country	Soil type	Bulk density (g cm^{-3})	
			CT	NT
Chaplain et al. (2011)	France	Silty soil	1.38[a]	1.33[a]
Constantin et al. (2010)	France	Haplic luvisol[b]	1.42	1.52
Crittenden et al. (2015)	The Netherlands	Clay loam	1.39	1.42
Garbout et al. (2013)	Denmark	Sandy clay loam	1.42	1.54
Hazarika et al. (2009)	England	Silty clay loam	1.21[a]	1.26[a]
Kechavarzi et al. (2009)	England	Sandy loam soil	1.45	1.47
Moncada et al. (2014)	Belgium	Sandy loam/silt loam	1.32[a]	1.28[a]
Schwen et al. (2011a,b)	Austria	Chernozem[b]	1.34	1.36
Ulrich et al. (2006)	Germany	Sandy loam	1.53	1.57

[a] These values are presented in mg m^{-3}.
[b] Classified according to the WRB (IUSS, 2006).

Table 3
Hydraulic conductivity from different NW European study sites comparing CT with NT systems (the values are based on the average of all observations from each of the studies).

	Country	Soil type	Saturated hydraulic conductivity
Crittenden et al. (2015)	The Netherlands	Clay loam	28.8% decrease under NT
Kechavarzi et al. (2009)	England	Sandy loam soil	10.8% increase under NT
Schwen et al. (2011a,b)	Austria	Chernozem[a]	15.9% decrease under NT
Schwen et al. (2015)	Austria	Chernozem[a]	98.3% decrease under NT
Ulrich et al. (2006)	Germany	Sandy loam	19.8% decrease under NT.

[a] Classified according to the WRB (IUSS, 2006).

tile drainage (Ulén et al., 2010), meaning that trade-offs have to be made in management decisions.

6.1. Purification

Studies addressing the effect of different farming practices on soil erosion and sediment inputs to water bodies agree with regards to the beneficial effects of NT compared with CT (Gaiser et al., 2008; Todorovic et al., 2014; Vogel et al., 2016). These findings may partly be explained by the higher aggregate stability of NT topsoils (Moncada et al., 2014; Urbanek et al., 2014), and the often more compacted surface, with higher bulk density (Knapen et al., 2007, ; Knapen et al., 2008b; Routschek et al., 2014; Van Gaelen et al., 2014, Nano et al., 2015) compared with ploughed and unprotected CT surfaces. Protection of the soil surface by crop residue and cover crops appears to be an important contributor to these results as well (Armand et al., 2009; Todorovic et al., 2014).

Some of the surface properties making the NT soils less erodible are also likely to contribute to lower infiltration capacity (Mueller et al., 2009; Rücknagel et al., 2017), decreasing the water purification potential. Although the infiltration rate can decrease under NT, some studies still show decreased amounts of surface runoff under NT practices as a result of soil surface characteristics (Leys et al., 2007; Hösl and Strauss, 2016), causing long runoff initiation times compared to soils under CT systems (Hösl and Strauss, 2016). This has implications for the transport of P. It can be suggested that NT practices have the potential to decrease total P inputs to water bodies, as it is mostly particle bound (Svanbäck et al., 2014) and thus transport by surface runoff will be restricted and P maintained on the fields.

Results from this review agree that the SS and total P load decrease under NT, while the DRP losses were shown to increase compared to soils under CT (Ulén and Kalisky, 2005; Ulén et al., 2010; Schoumans et al., 2014). DRP has greater impact on water quality than PP, even in low concentrations, due to a higher bioavailability (Schoumans et al., 2014). However, in the longer term PP can be at least partly released and taken up by biota, so Schoumans et al. (2014) suggested that a balance between the focus of reducing DRP and PP should be considered. Soils that are sensitive to erosion due to topography (slope), fine soil texture and low particle cohesion (e.g. silty soil with low organic content) can benefit from a NT system, while such a system is not recommended for soils that are more sensitive to leaching (e.g. as to accumulated surplus P and SOM in the top soil) (Fig. 3). However, a high spatial variability even within the same field can be expected with nutrient leaching due to different soil properties and moisture content, making nutrient leaching difficult to quantify.

The increased losses of DRP from NT systems can be partly explained by the increased amounts of vegetation covering the soil surface in these systems compared to CT where the surface is bare. Accumulation of nutrients on the top soil caused by cover crops or weeds sprayed by glyphosate or damaged by frost are important sources of nutrient leaching and loss of DRP (Ulén and Kalisky, 2005). Another possible explanation is higher nutrient stratification to topsoils under NT compared to CT, where the distribution in the plough layer is more uniform due to soil inversion (Schoumans et al., 2014; Martínez et al., 2016). Limiting DRP inputs to water bodies is key to achieving objectives set by the WFD, as nutrient enrichment and eutrophication is one of the greatest threats to water quality (Carpenter et al., 1998; Hilton et al., 2006). Although erosion rates and loss of particulate P are likely to decrease, no such reduction in N leaching was found. Cover crops, on the other hand, in combination with NT, demonstrated good potential to mitigate leaching due to a higher N uptake (Constantin et al., 2010; Cooper et al., 2017).

Cover crops have been found to be crucial to enhance the performance of NT farming, and reduce potential drawbacks such as poor soil porosity and friability, N leaching and compaction (E.g. Bechmann et al., 2008; Bodner et al., 2013; Abdollahi et al., 2014; Burr-Hersey et al., 2017; Cooper et al., 2017). However, the type of crop has to be considered (Bodner et al., 2008; Aronsson et al., 2016), and the impact largely depends on the type of rooting system in combination with degree of canopy coverage (Bodner et al., 2010); knowledge about local conditions and site-specific challenges is essential when selecting cover crop species. For instance, a soil suffering from topsoil compaction is likely to benefit from a cover crop with thick roots that can contribute to structural remediation of the soil (Burr-Hersey et al., 2017).

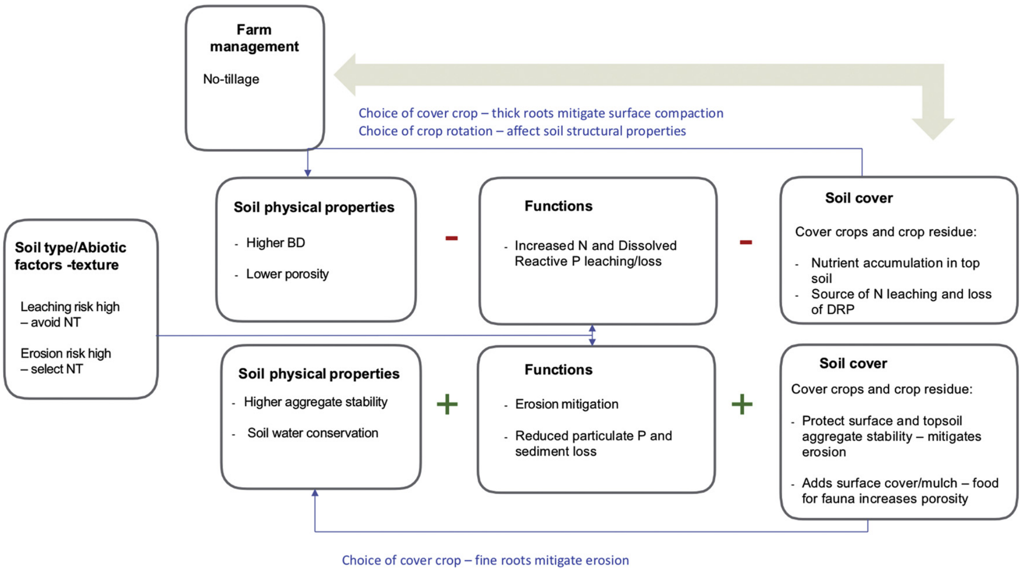

Fig. 3. Overview of the impact of NT farm management on soil physical properties and water related soil functions, and under what conditions NT practices are recommended. The red minus signs represent degradation and the green crosses conservation.

Whereas, highly erodible soils may benefit more from fine branched, high density roots that can help bind the soil (De Baets et al., 2011). Legumes species can fixate N to plant available forms, and can therefore reduce the need for fertilisers, but these should be used with caution in soils sensitive to leaching (Aronsson et al., 2016). Cover crops are beneficial to mitigate total P loss as soil surface cover reduces erosion and PP concentrations in surface runoff. The effect is however lower for P than N as desorption of P from particles is a slow process.

6.2. Water retention

Several studies confirm that NT soils have the potential to hold higher water content than soils under CT (e.g. Urbanek et al., 2014; Kainiemi et al., 2015; Ugarte Nano et al., 2016). In situations where soil water is a limiting resource, the ability to conserve water could be important for crop growth and maintenance during periods of draught (Schwen et al., 2011a). When the soil is more likely to have a water surplus (i.e. due to more humid conditions) the excess water can also be a challenge. Heavy machinery on saturated soils is a major contributor to compaction damage (Lipiec and Hatano, 2003) which can decrease the number of days suitable for field operations. This is significant for wetter NW regions of Europe Moreover, wet and poorly-drained NT soils have greater denitrification, which leads to higher emissions of the greenhouse gas NO_2 (Rochette, 2008). The cumulative impact of implementing NT practices are therefore very much dependent on climatic conditions in combination with soil type and other local variables.

6.3. NW Europe

Soane et al. (2012) reviewed the opportunities and problems for crop production and the environment under NT for northern, western and south-western Europe. Their findings suggest an increasing uptake of the practice in south-western Europe driven by financial savings in tillage costs and to maintain yields during hot and dry summers, as less soil disturbance and high residue coverage reduces evaporation from the soil. They also report limited uptake in northern and western parts of Europe, and the importance of well drained NT soils under wet conditions. Although their study focuses more on crop yield and less on water functions, it underpins the results in the current review by comparing findings from different parts of Europe rather than amalgamating them, thus highlighting the importance of local conditions and climatic factors. In general, there are more studies focusing on yield than the rest of the soil functions.

6.4. Water Framework Directive

In implementing the WFD, phosphorus, nitrogen, sediment and turbidity are important in managing the risk of adverse ecological impacts, and these are monitored against national standards, for example in the UK (UK legislation, 2015). Understanding the effect of agricultural practices such as NT on these is therefore important.

This review has shown that there is consensus about reduced erosion rates under NT practices, with the accompanying potential to decrease sediment loads and particulate P inputs to water bodies, although it has also shown that NT can lead to increased loss of DRP and N leaching. Furthermore, it has been demonstrated that cover crops can ameliorate some of the limitations of NT in certain situations. It is clear however that the effects are largely dependent on context and management. It is not possible therefore to recommend wide-scale use of NT with the primary goal of achieving WFD goals. Nevertheless, in certain situations, e.g. where erosion and PP are a particular concern for ecological status, NT should be considered. Although implementation is not recommended on soils sensitive to leaching (Schoumans et al., 2014). In some cases other practices such as reducing fertiliser use and P mining (through zero application of P) in sensitive areas, is probably more efficient to reduce DRP losses than NT (Whitehead et al., 2014; Van Grinsven et al., 2016). In a review assessing results from ten Swedish long-term studies Bergstrom et al. (2015) identified liming, incorporation of manure into soil and small constructed wetlands as efficient measures to reduce drainage losses of P from clay soils in a cold climate. The P level in soils should ensure efficient P use by crops to minimise the risk of losses to the environment. This is in line with the principles of WFD, which recognises the complexity of ecosystems and the interactions and trade-offs at different scales; and acknowledges that catchments differ from each other in terms of natural and agricultural conditions (Voulvoulis et al., 2017).

6.5. Limitations

The review did not focus on the often increased need for pesticide usage amongst NT farmers (Tørresen et al., 2003; Soane et al., 2012), and what impact that may have on surface and ground water. Herbicides (i.e. glyphosate) are necessary for weed control, which can be more problematic in NT than CT soils due to the absence of soil inversion (Tørresen et al., 2003). Whether NT soils are more likely to experience leaching of nutrients and pesticides to ground water aquifers as a result of higher occurrence of deep vertical macropores, due to vertically drilling earthworms, is also interesting from a water management point of view.

Scale is another limitation, as a high number of the studies in this review are carried out on plot scale, the effect of practices on farm or catchment scale often remain uncertain unless predicted by modelling. The WFD stresses the importance of having a whole catchment approach when managing freshwater resources, but upscaling from plot to catchment scale is complicated and dependent on many variables.

Knowledge about the effect of NT practices on the remainder of the soil functions is important to understand the total impact of the farming system. A comprehensive review of all of the soil functions is beyond the scope of a single review, and therefore in this review the focus was on water related functions. However, the trade-offs between different soil functions under NT should therefore be assessed in future reviews, to see if the practice benefits some functions but disadvantages others.

7. Conclusion

The aim of this review was to investigate results from recent studies of NT practices carried out in NW Europe and assess how they are affecting the water purification and retention functions of the soil. Although the reviewed literature presented some conflicting findings regarding the benefits and drawbacks of implementing NT practices, there seems to be consensus on some characteristics relevant to these soil functions. Our analysis of the literature in this review paper allows for the following considerations and recommendations:

Firstly, the literature consistently demonstrates a beneficial effect of reduced erosion rates under NT practices. Decreased soil loss from agricultural fields has the potential to decrease sediment loads and particulate P inputs to water bodies. Nevertheless, the losses of bioavailable DRP is likely to increase under NT, and the effect on other soil properties like hydraulic conductivity, infiltration and water holding capacity is more uncertain, and more dependent on local site conditions; this is an area that needs to be explored further in field investigations.

Secondly, there is a consensus that NT does not reduce N leaching, unless combined with a cover crop. The potential of cover crops in reducing N leaching is greater than for reducing P due to the faster uptake of N by both crops and cover crops. However, the effect varies largely with the type of crops, soil type and climatic conditions.

Thirdly, cover crops are important in enhancing the performance of NT and in reducing potential limitations. It is therefore important to conduct detailed assessments of the soil and local conditions before introducing new farming practices. The addition of cover crops to NT systems is mostly beneficial (e.g. by protecting the soil surface from erosion, reducing N leaching, creating better habitat for biodiversity like earthworms, mitigating compaction damage of the top soil and suppressing weeds), but the type of cover crops is important. Root and canopy characteristics vary largely between species, and when establishing a cover crop the farmer should consider the specific challenges and needs for that particular soil (e.g. a cover crop with fine branched roots to protect the top soil from erosion, or thick and deep roots to mitigate problems with topsoil compaction). However, enrichment of P near the soil surface increases the risk for DRP losses and increased organic matter in the top soil may further enhance the desorption of Phosphate, representing a trade off between the mitigation of PP losses by erosion and leaching of DRP from dead and damaged plants.

Fourthly, there is no consensus that NT can increase water retention since this effect is highly dependent on soil texture, climatic conditions and other management factors. NW Europe faces particular challenges as the weather conditions can make the implementation of NT practices more difficult. Instead of having a water deficit, which is often the case in the countries where NT is more widespread, the climate is both colder and wetter through large parts of the year. As climatic factors are important to field operations and crop establishment, there is still a need for further assessment of the practice in NW Europe conditions and considering the impacts under future climate change scenarios. The contribution of NT practices to achieve WFD water management objectives in NW Europe is still uncertain and more research is required to understand the trade-offs between different soil functions under NT in different contexts.

Author contributions

The authors have no competing interests to declare. All authors conceived the idea and contributed to the planning. KS undertook the literature searching and analysis and lead on the writing. All authors contributed critically to the drafts and gave final approval for publication.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.still.2019.01.004.

6 Paper II

Impact of no-tillage on water purification and retention functions of soil

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Abstract:

There are still uncertainties regarding the long-term impact of no-tillage farming practices on separate soil functions in the United Kingdom. This paper aimed to evaluate the chemical and physical processes in two different agricultural soils under no-tillage and conventional management practices to determine their impact on water related soil functions at field scale in the United Kingdom. The field-scale monitoring compares two neighbouring farms with similar soil and topographic characteristics; one of the farms implemented no-tillage practices in 2013, while the second farm is under conventional soil management with mouldboard ploughing. Two soil types were evaluated under each farming practice: (1) a free-draining porous limestone, and (2) a lime-rich loamy soil with high silt and clay content. Field monitoring was undertaken over a 2-year period and included nutrient analysis of surface and sub-surface soil samples, bulk density, soil moisture, infiltration capacity, surface runoff and analysis of Phosphorous and suspended solids in watercourses in close proximity to the test fields. The conversion to no-tillage changed the soil structure, leading to a higher bulk density and soil organic matter content and thereby increasing the soil moisture levels. These changes impacted the denitrification rates, reducing the soil Nitrate levels. The increased plant material cover under no-tillage increased the levels of soil Phosphate and Phosphate leaching. The extent to which soil functions were altered by farming practice was influenced by the soil type, with the free-draining porous limestone providing greater benefits under no-tillage in this study. The importance of including soils of different characteristics, texture and mineralogy in the assessment and monitoring of farming practice is emphasised, and additionally the between field and in-field spatial variability (both across the field and with depth), highlighted the importance of a robust sampling strategy that encompasses a large enough sample to effectively reveal the impact of the farming practice.

Keywords:
monitoring scale–no-tillage–soil functions–soil structure–water purification–water retention

Farmers are reliant on soil health to maintain and improve their productivity, they are therefore constantly looking to develop and improve their practice to suit the local conditions and to increase yield. This constant evolving of farming practices to changing conditions (Cock et al. 2011; Scoones and Thompson 1994) has formed the basis of farming innovation that is led by the farmers themselves (Cock et al. 2011), but formal information from research also has an important role in improving and developing aspects of the agricultural landscape (Hall 2005). Intensive farming practices such as conventional tillage (CT) farming with moldboard ploughing is beneficial for weed supression and plant growth, as loosening and inverting the soil causes a higher degree of oxidation and mineralization transitioning nutrients to plant available forms. These processes can, however, lead to an exelerated breakdown of organic compounds (Balesdent et al., 2000) and make the soil more vulnerable to erosion, also as it is left bare and unprotected by plant material (Lundekvam, 2007, Vogel et al., 2016). This has led to an increase in the uptake of alternative and less intensive farming practices to reduce the frequency of soil disturbance to avoid long term soil degradation by erosion and soil organic matter (SOM) losses, and to maintain soil fertility and the environmental functions of the soil (Reicosky 2015). Soil resources are multi-functional and have an important role in providing a wide range of regulating and production functions crucial to ecosystems (Greiner et al. 2017). These soil-based ecosystem services are often referred to as 'soil functions' (Schulte et al. 2014; Dominati et al. 2010) and are multi functional; the soils' ability to deliver these different functions vary with variables such as soil properties, climate and management practices. The dynamics between them are complex and farming practices can have a positive effect on some soil functions, while negatively impacting others (Valujeva et al. 2016).

No-tillage (NT), also referred to as “zero tillage” or “direct drilling”, is a low disturbance farming practice without soil inversion (Townsend et al. 2016), and is often carried out in combination with other management practices such as crop residues, cover crops and different crop rotations (Brooker et al. 2015; Döring et al. 2005; De Baets et al. 2011; Skaalsveen et al. 2019; Sharma et al. 2018; Unger and Vigil 1998). NT practices are becoming more widely used in farming and are often considered to enhance soil functions and soil structure (Skaalsveen et al. 2019; Bertrand et al. 2015; Crotty et al. 2016). Studies indicate that NT has a particularly positive effect on the soil water purification and water retention function as the accumulation of SOM in the topsoil improves the aggregate stability of the soil (Teasdale 2007); which is an important soil structure variable, impacting the resistance to erosion and compaction (Urbanek et al. 2014) and reducing soil and nutrient losses from agricultural fields to water bodies by soil erosion (Schoumans et al. 2014; Mhazo et al. 2016). However, supporting evidence from sites within north western Europe is still limited and more research is required to fully understand the relationships (Skaalsveen et al. 2019; Soane et al. 2012). In particular, knowledge about the effect of soil management practices on separate soil functions is necessary to understand potential trade-offs between functions (Valujeva et al. 2016) and to what extent, and under what conditions, NT farming can be seen as a sustainable soil management option.

Soil type and climate are two of the most important factors influencing farmers’ decisions relating to the type of tillage practice implemented. Alskaf et al. (2020) and Powlson et al. (2012) found that the principal reason for the lower conversion to NT across north western

Europe than in the Americas and Australia, where the practice is more widespread, is the build-up of grass weeds, crop disease problems and soil compaction that seems to occur with more temperate climates. NT is primarily practiced in areas with calcareous clay soils in the United Kingdom (UK) because they self-mulch as a result of wet-dry and freeze-thaw cycles which produces good tilth in a way that does not occur with other soil types (Powlson et al. 2012). Additionally, these soils tend to be associated with good drainage and naturally stable structure that is most suited for reduced tillage (Davies and Finney 2012). In drier areas of the UK clays are more suited for reduced tillage practices as free draining loams tend to over-compact (Carter 1987; Davies and Finney 2012), the latter are suitable soils in wetter areas of the UK resulting from higher SOM contents that provide higher soil stability (Davies and Finney 2012).

When evaluating the impact of a change in farming practice timescale has to be considered; both in terms of frequency of data collection and ensuring that enough time has occurred since the implementation to allow process change to occur. Peukert et al. (2013) suggested a time lag of at least five years from starting an experiment to seeing the outcome; this is somewhat problematic as scientific projects often have a shorter life span. The spatial scale that monitoring is undertaken at is also an important consideration. Operational on-farm experiments are important as factorial experiments might not predict the performance of the whole system and lead to incorrect conclusions. The on-farm approach has the advantage of studying systems that are realistic in terms of scale, management practice and constraints faced by the farmer (Drinkwater 2002). Depending on the characteristics of an area the impact of change can vary between farms and therefore when evaluating changes to farming practice care must be taken when applying results from one farm to another (Maillard et al. 2017; Pribyl 2010).

There are several factors that need to be taken into account when considering scale related to the farm management (e.g. historical management of the farm), human factors (i.e. different farming ‘styles’ and timings of different farmers), abiotic factors (local weather and topography), underlying geology, soil type (texture, organic content, particle fraction size and soil depth) that affect the properties (soil structure, hydraulic conductivity, water retention, water infiltration and soil erodibility) and the vegetation cover. Additionally, within field variations in soil properties can also be significant and often poorly understood (Paukert et al. 2013). The spatial variation on a field level is normally explained by a single factor such as soil characteristics or local pest outbreaks, while factors like management and weather conditions are constant over the whole field and more important when comparing between management units (Cook et al. 2011).

This paper aims to evaluate the chemical and physical processes in two different agricultural soils under different management practices (NT and CT) to determine their impact on water related soil functions at field scale. In our study we focus on the slow response variable of soil structure, and therefore an operational research method makes sense in this context as we benefit from collecting samples from well-established farms which have practiced the same system for a long enough time period to reach a steady-state condition that is more comparable (Drinkwater 2002), while starting up a new experiment would be challenging and affect the reliability of the results with a data collection period of only a couple of years.

The objectives are as follows:

(1) To compare soil physical and chemical variables and the water infiltration and retention functions of soils under different farm management practices (NT and CT);

(2) To determine the influence of different soil types on the benefits and drawbacks of the different farm management practices on soil functionality;

(3) To compare the spatial and vertical variability of soil physical and chemical variables in fields of different soil types and management to determine the in-field variability.

Methods and Materials

Study Site The research was undertaken at Bredon Hill (52°03′37″ N, 2°03′46″ W) in Worcestershire in the UK (figure 1). The area is an outlier of the Cotswold escarpment and has a maximum elevation of 299 m (981 ft), average annual temperature of 9.7°C (49.5°F) and annual precipitation of 660 mm-1 (25.9 in-1) (Climate-data 2019). The upper elevations are formed of the Birdlip Limestone Formation, associated with Cotswold Brash soils (Calcaric Endoleptic Cambisols (Cranfield University, 2020; IUSS, 2007)) typified by its high content of free-draining porous limestone (up to 50% of the soil volume) and shallow depth, while the lower elevations consist of the Charmouth Mudstone Formation, associated with lime-rich loamy soils (Calcaric Stagnic Vertic Cambisols (Cranfield University, 2020; IUSS, 2007)) with a medium to high silt content and the presence of calcareous Jurassic clays which have low permeability and are exposed to water logging (British Geological Survey 2018).

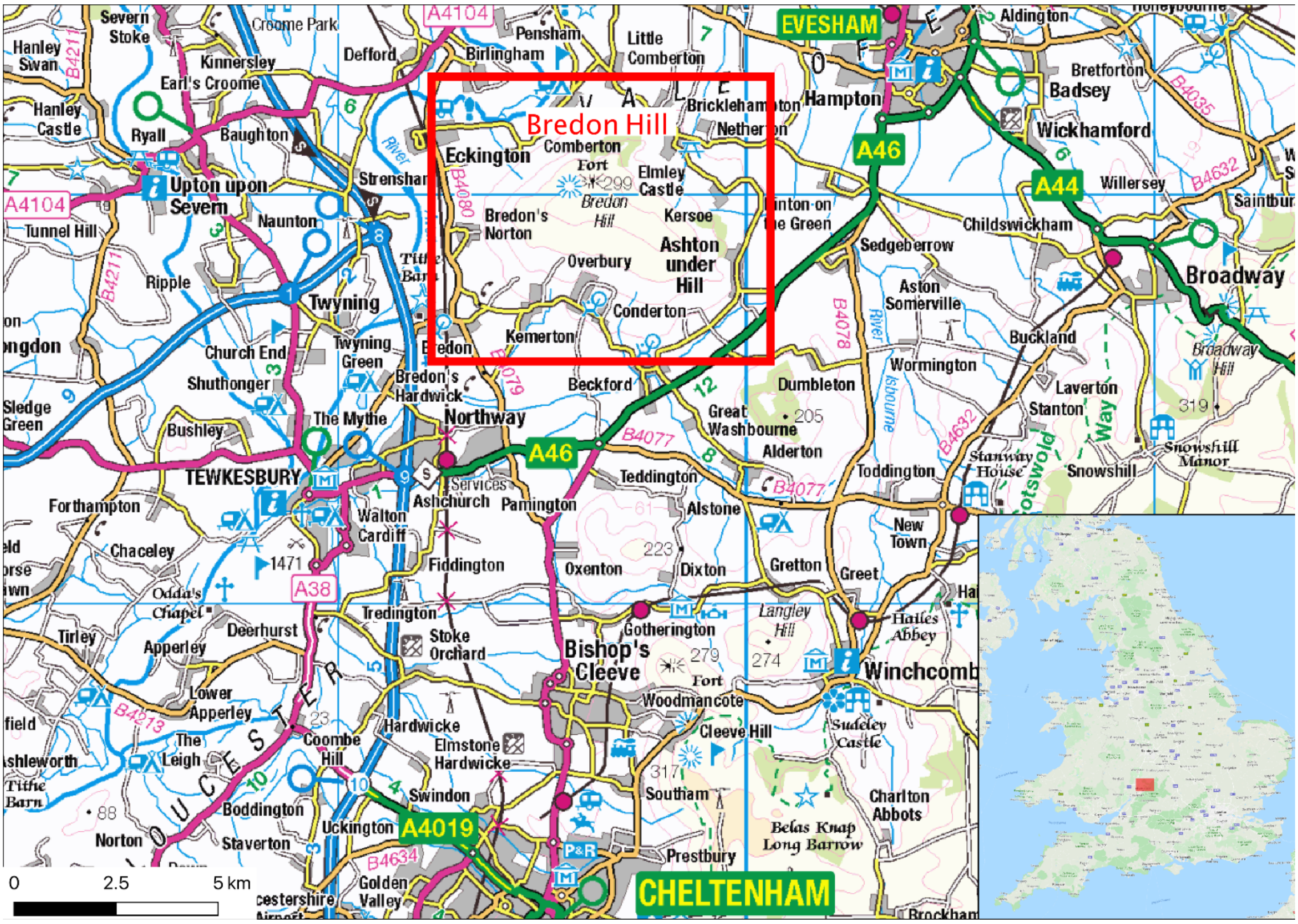

Figure 1. Study site location in Bredon Hill, Worcestershire, UK (outlined by red box).

Experimental Fields The monitoring was undertaken at two neighbouring commercial farms that had similar soil types (one field of Cotswold Brash and one field of lime-rich loamy soil assessed at each farm) and topographic conditions; one that used CT and the other converted to NT with direct drilling in 2013. Measurements were carried out from 2018 to 2019, with detailed sampling undertaken in Spring (April and May) and Autumn (September and October) of 2018 and the Spring (April and May) of 2019 to coincide with periods of crop changeover on the two farms. To account for the distinctive soil boundary in this area, the sampling strategy consisted of four fields with one field of each soil type at each of the farms. A comprehensive grain size distribution analysis was carried out with nine samples from each field consisting of soils from 0 to 50 cm (0 to 19.7 in) depth that were analysed by a Malvern Mastersizer range particle size analyser.

Tillage Treatments The NT farm implemented direct drilling in 2013 after a transition period of reduced tillage from 2004, these practices included crop protection by crop residue management and cover crops (occasionally grazed off by sheep). The CT farm cultivates the soil by mouldboard ploughing but transitioned to minimum tillage in 2017 in the lime-rich loamy field (CT-C).

The four monitoring sites were as follows:

1) NT-S: NT farming practices on Cotswold Brash (10 to 13% clay (<0.002 mm), 26 to 36% silt (0.002 – 0.063 mm), 3 to 13% sand (0.063 – 2 mm) and approximately 50% coarse fragments (>2 mm)) with pH = 8.1. Farming practices included: direct drilling, cover crops and soil cover by crop residue with wheat and oil seed rape rotation (forage turnips grazed by sheep Autumn 2017). Average slope: 6.1%. Aspect: Southeast facing slope.
2) NT-C: NT farming practices on lime-rich loamy soils (27 to 33% clay (<0.002 mm), 50 to 65% silt (0.002 – 0.063 mm), 7 to 22% sand (0.063 – 2 mm) and no coarse fragments (>2 mm)) with pH = 6.9. Farming practices included: direct drilling, cover crops and soil cover by crop residue with wheat and peas rotation. Average slope: 0.6%. Aspect: South facing slope.
3) CT-S: CT farming practices on Cotswold Brash (11 to 14% clay (<0.002 mm), 25 to 30% silt (0.002 – 0.063 mm), 8 to 14% sand (0.063 – 2 mm) and approximately 50% coarse fragments (>2 mm)) with pH = 8.1. Farming practices included: Mouldboard ploughing with spring barely rotation (forage turnips grazed by sheep Autumn 2018). Average slope: 12.8%. Aspect: Southwest facing slope.
4) CT-C: CT farming practices on lime-rich loamy soils (26 to 31% clay (<0.002 mm), 56 to 64% silt (0.002 – 0.063 mm), 7 to 13% sand (0.063 – 2 mm) and no coarse fragments (>2 mm)) with pH = 8.1. Farming practices included: Mouldboard ploughing with recent transition to minimum tillage with wheat, oil seed rape, wheat and beans rotation. Average slope: 5.7%. Aspect: Southwest facing slope.

Field and Laboratory Methods The following variables were measured during the monitoring period. All measurements are recorded in metric units, where 10 cm is equal to 3.9 in.

Water Infiltration The infiltration rate (i.e. the speed at which water enters the soil) of each of the fields was measured using a double-ring infiltrometer. This was conducted at a single location in each field and in both the north-western and south-eastern end of NT-C, in Spring 2018, Autumn 2018 and Spring 2019.

Soil Organic Matter (SOM) and Soil Moisture Soil samples for SOM and soil moisture were collected monthly from two depths (0 to 10 cm and 10 to 20 cm) at nine sampling locations in the NT fields from 2015 to 2017. During the more detailed sampling regime in 2018 and 2019 soil samples were collected from nine sites in all fields, except CT-C where they were collected from six sites, and from five depths (0 to 10 cm, 10 to 20 cm, 20 to 30 cm, 30 to 40 cm and 40 to 50 cm).

SOM was calculated using the loss-on-ignition method where the dry sample was burned at 550°C (1022°F). To determine the soil moisture, the water content was determined by oven-drying 5 g of wet sediment sample at 105°C (221°F) and recording the difference in weight between the wet and dry sample.

Bulk Density Bulk density (i.e. the weight of soil in a given volume) samples were collected in Spring 2018, Autumn 2018 and Spring 2019 from three locations on each field (only two from CT-C) and from two depths at each location (surface: 0 to 10 cm and sub-surface: 15 to 25 cm). The sampling was carried out by the excavation method which was more suited for soils with a high content of rocks or gravels (such as the Cotswold Brash) than the standard core method. This consisted of digging a hole in the soil and sieving out all material greater than 2 mm (0.08 in) in size, the volume of the pit was measured by lining it with plastic wrap, placing the sieved rocks and gravel back inside and adding water from a syringe. The water volume was then recorded and the soil samples were oven dried and weighed in the laboratory and the following equations applied:

Soil bulk density (g/cm3) = weight of oven-dried soil / volume of soil

Soil water-filled pore space (%) = (volumetric water content x 100) / soil porosity

Volumetric water content (g/cm3) = soil water content x bulk density

Soil porosity (%) = 1 – (soil bulk density / 2.65)

Soil Nutrients Soil nutrient samples were collected using the same sampling strategy as outlined above. Ammonia (NH3) and Nitrate (NO3) samples were extracted by shaking the soil sample with a 2M KCl solution, filtering and analysing by the use of a continuous flow AA3 Seal AutoAnalyzer with a colorimetric determination of dissolved nutrients. The soil orthophosphate (PO43-) was extracted by the Olsen P method, filtered and analysed by the colorimetric method (molybdate) with a spectrophotometer.

Stream Water Quality Water samples were collected from ten sampling locations in March and May 2018. The streams were running through or downstream of the two farms (five sampling locations per farm) and sampling took place in March and May 2019 after longer rainfall events to make sure that there was enough water in the smaller streams during sampling. The samples were filtered by a 50 ml plastic syringe (sterile) with filter attachment containing a cellulose Nitrate filter (0.45 □m). The Phosphate (PO4) and Phosphorous (P) analysis were carried out by the University of Exeter using a Seal Analytical AutoAnalyzer (4 Channel Serial) providing the Total Phosphorous (TP) and Dissolved Reactive Phosphorous (DRP).

Statistical Analysis Rstudio (version 1.1.463) software was used for statistical analysis of the data. A nested ANOVA was carried out for variance analysis of the different variables nested within the different fields within the farming practices (e.g. for differences in concentrations of SOM and nutrients with sampling depth for each practice or soil type). A one-way ANOVA was used for the variance analysis of within-field values, and a Tukey multiple pairwise-comparison analysis was carried out to compare values between fields. Pearson's correlation tests were carried out for correlations between variables, while Principle Component Analysis (PCA) was used to determine the variance and find the quality of representation of different variables.

Results and Discussion

Farming Practice: Comparison of No-tillage (NT) and Conventional Tillage (CT) Farming

SOM levels are an important indicator for soil structure and aggregate stability (Schoumans et al. 2014; Mhazo et al. 2016; Teasdale 2007), and Kreiselmeier et al. (2019) found higher temporal stability of soil structure and comparably lower transmission (water movement) but more retention (storage pores) under NT than under reduced tillage and CT. This meant that the soil structure of NT was more resilient to erosion with regards to precipitation extremes than under CT, with comparably low bulk density and high porosity favouring rapid infiltration (Golabi et al., 1995). In this study, there were no significant differences between the bulk densities of the two practices (NT vs. CT) ($p > 0.05$), but there were significant differences between separate fields. The bulk density of CT-C (with the lowest mean bulk density) was significantly lower ($p < 0.05$) than of NT-C (table 1). This reflected the higher compaction of topsoils that often occur under NT as it is not loosened with a plough as under CT.

Table 1. Structural properties of the four test fields measured in Spring 2018, Autumn 2018 and Spring 2019.

Date	Field	Bulk Density (g/cm3)	Soil porosity (%)	Soil water content (g/g)	Volumetric water content (g/cm3)	Soil water-filled pore space (%)	Infiltration rate (mm/min)
Spring 18	CT-C	1.03 (±0.127)	0.61	0.25	0.26	42.4	†
	NT-C	1.28 (±0.121)	0.52	0.24	0.31	60.1	0.35
	CT-S	1.51 (±0.294)	0.43	0.18	0.27	63.4	0.50
	NT-S	1.17 (±0.199)	0.56	0.21	0.24	43.4	1.4
Autumn 18	CT-C	1.03 (±0.128)	0.61	0.26	0.27	43.6	0.40
	NT-C	1.37 (±0.141)	0.48	0.27	0.37	76.7	0.35
	CT-S	1.31 (±0.246)	0.51	0.17	0.23	44.6	0.80
	NT-S	1.32 (±0.157)	0.50	0.24	0.32	63.1	1.5*
Spring 19	CT-C	1.14 (±0.087)	0.57	0.22	0.25	43.8	0.40
	NT-C	1.27 (±0.173)	0.52	0.22	0.28	54.3	0.50
	CT-S	1.22 (±0.131)	0.54	0.19	0.23	42.3	0.70
	NT-S	1.03 (±0.262)	0.61	0.22	0.23	37.1	1.0

*Unstable and rapid infiltration (flow did not properly stabilise).

†Not possible to record any accurate infiltration measurements as the field was extremely dry and contained large cracks which the water flushed through.

The Tukey multiple pairwise-comparisons showed that significant differences in SOM only occurred between NT-S and the three other fields (with significantly higher SOM levels ($p < 0.001$) in NT-S), while no significant difference was found between NT-C, CT-S and CT-C (figure 2). The mean SOM level of NT-S was 9.2 %, while the lowest mean SOM level of 7.1% occurred at CT-S.

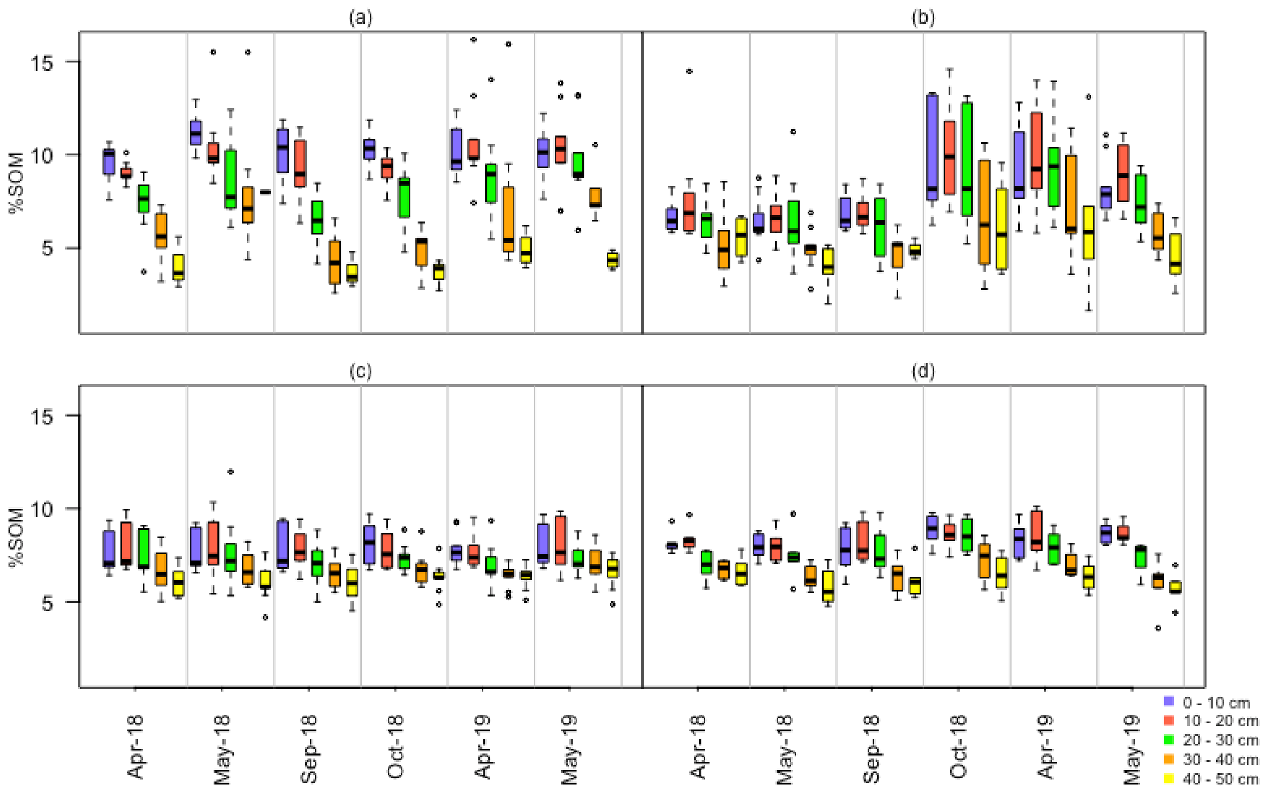

Figure 2. Soil organic matter (SOM) levels at (a) NT-S, (b) CT-S, (c) NT-C, and (d) CT-C at different depths sampled (represented by the different colours; key provided below) from Spring 2018 to Spring 2019 showing mean values and 75% confidence intervals.

Higher soil moisture levels are often expected under NT as the crop residue and soil structure reduce the evaporation from the field, thus the total ecological respiration tends to respond more intensely to rainfall events under CT than NT (Chi et al. 2016). The soil water-filled pore space from our study agreed with this (table 1), with NT fields (mean value: 55.8%) higher than CT fields (mean value: 46.7%). This ability to retain soil moisture is an advantage in soils exposed to drought. NT was originally developed to conserve moisture during a drought period in Central and South America (Kassam et al. 2012; Lahmar 2010); as shown with our study where soil retention was higher in NT fields following a water scarce period in summer 2019 (average values for soil water-filled pore space: NT = 69.9%, CT = 44.1%).

Nevertheless, high soil moisture content can be a challenge in areas with a wetter climate and can restrict the window of opportunity for field operations and increase the risk of soil compaction. This was supported by other studies that found poorer soil structure and higher compaction in NT fields compared to CT (Peigné et al. 2009; Peigné et al. 2013 Franzluebbers et al. 1995). There can be temporal variability in bulk density values (Wuest 2015) and Franzluebbers et al. (1995) found differences in bulk density values between CT and NT with large seasonal dependence. The largest variation was found under CT as the bulk density decreased due to tillage but increased with time after tillage to the level of NT resulting from densification processes, causing more changes in the physical condition of the CT soil.

In our study, elevated bulk density values were found in the two NT fields during Spring 2018 (table 1). In an American study where the relationship of bulk density and water table depth with soil properties were compared at 16 study sites, Logsdon (2012) found a negative correlation between volumetric water content and bulk density, but mainly on dry dates and not wet dates. This is one possible explanation for the elevated bulk density values found in the two NT fields in November 2018 (table 1) as these fields retained a higher level of the soil moisture over what was an extended period of dry conditions (Summer 2018).

There was an increase in the NO3 concentrations in the two CT fields (figure 3). The Nitrogen (N) cycle is complex and a number of conditions determine the forms of N, such as the amount of fertiliser applied by the farmer. However, other likely explanations for the lower NO3 concentrations in the NT fields was that denitrification processes often increase with higher SOM levels, meaning that NO3 was reduced to gaseous forms of N (primarily N2O and N2) by microbes. Denitrification was also a likely outcome of anaerobic conditions as a result of high soil saturation or increased bulk density (due to less aeration). This has been confirmed by earlier studies (Constantin et al. 2010; Rochette 2008) that demonstrated increased N2 emissions under NT management.

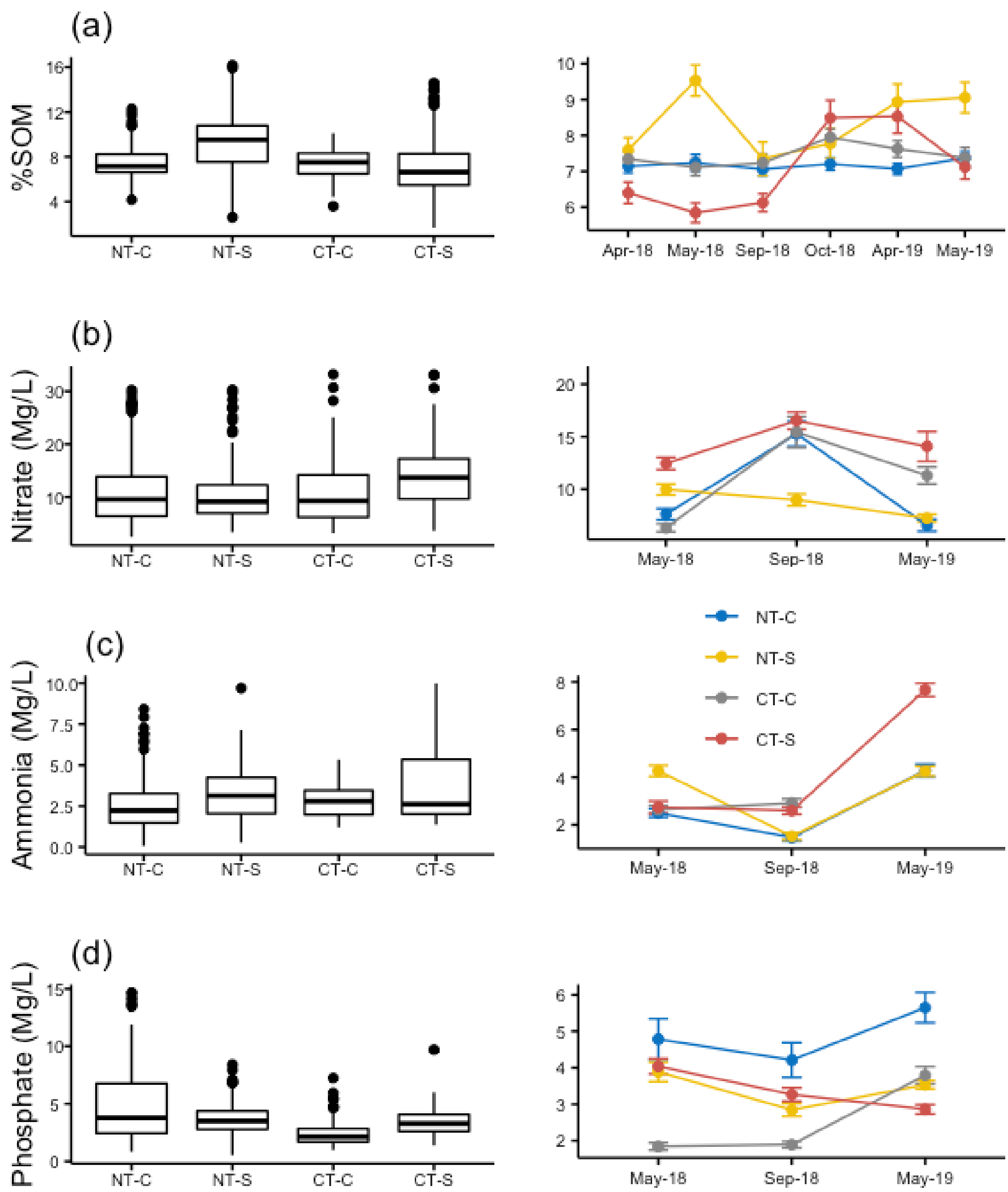

Figure 3. Mean values with 75% confidence intervals of (a) soil organic matter (SOM), (b) Nitrate (NO_3), (c) Ammonia (NH_3) and (d) Phosphate (PO_4^{3-}) for the four fields (shown on the left) and plotted temporally between Spring 2018 and Spring 2019 (shown on the right).

No significant trends were found for the NH3 concentrations between practices (figure 3), while the highest concentrations of soil PO43- were found in the NT fields (NT-C = 4.86 mg/L and NT-S = 3.68 mg/L), with the lowest level at CT-C (2.50 mg/l). The concentrations measured at NT-C were significantly higher than for all three of the other fields ($P < 0.001$) and there were significant differences between soil PO43- concentrations for all of the combinations of fields apart from between NT-S and CT-S. The increased soil PO43- levels under NT was probably a result of the increased input of plant material and crop residues under this practice, this increased the TP and organic P concentrations which in turn can increase the activities of phosphatase, which is the mechanism that makes P available to plants (hydrolysed into PO43-) (Wang et al. 2011). However, other scholars have found that the most important effect of different tillage practices on soil P is the stratification to the topsoil layer resulting from crop residues, fertilisation and the lack of mixing (Tracy et al. 1990), so the increased overall PO43- levels in this study was also a likely result of differing fertilisation regimes between the farms.

With regards to the water samples, there were higher levels of total P downstream of the NT fields (mean: 0.547 mg/L) than those collected downstream of CT (mean: 0.166 mg/L) shown in figure 4a, however, this was partly caused by a highly elevated concentration at the O2 (NT) sampling location in March 2019 (3.699 mg/l). The difference between the streams downstream of NT and CT fields was greater for DRP concentrations (NT = 0.188 mg/L, CT = 0.0316 mg/L) shown in figure 4b. The concentrations of TP and DRP were generally higher in May (Summer-time) than in March (Spring-time), probably as a result of elevated water discharge during the sampling in May causing a dilution effect.

a) **b)**

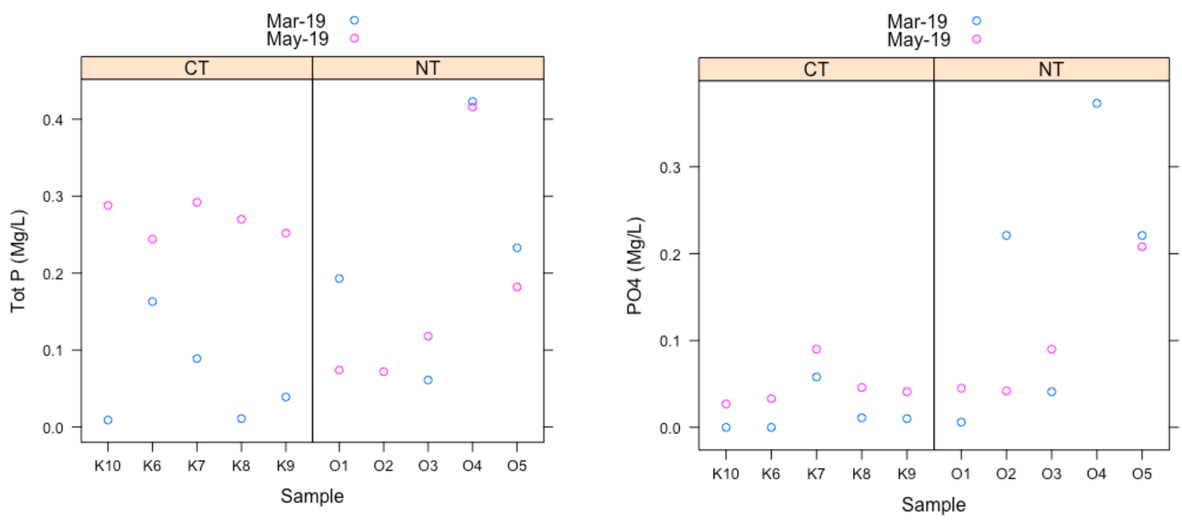

Figure 4. Concentrations of (a) Total Phosphorous (TP) and (b) Dissolved Reactive Phosphorous (DRP) in water samples collected from streams in close proximity to the no-tillage (NT) and conventional tillage (CT) farms in March (blue) and May (pink) 2019.

The P loss potential can vary both with soil type and practice (Li et al. 2019). Previous research has analysed the differences in P inputs from different farming practices and found that the decreased erosion rates expected under NT (with more soil protection) also reduced the TP inputs to downstream waters as a large fraction of the total P is bound to particles (Svanbäck et al. 2014; Ulén and Kalisky 2005; Ulén et al. 2010; Schoumans et al. 2014). However, studies have also found that the concentration of DRP can increase downstream of NT fields, in accordance with the findings in this study, which can therefore have implications on the water quality as this form of P is highly reactive (Ulén and Kalisky 2005; Ulén et al. 2010; Schoumans et al. 2014). Increased DRP concentrations by the NT fields can be a result of leaching through vertical water movement through the soil (Daniel et al. 1994) and then entering watercourses via tile drainage (Ulén et al. 2010). The increased risk of DRP losses from NT fields can be explained by the increased enrichment of nutrients in the topsoil under this practice (Taylor et al. 2016) and releases of DRP from the plant material that is accumulated on the soil surface (cover crop and crop residues) (Ulén et al. 2010). The elevated concentrations of soil PO43- found in the NT fields compared to the CT fields was also a likely contributor to the higher values of P in the water samples downstream of these fields.

Similar patterns as found for P were also true for N, and in a long-term field experiment Autret et al. (2019) compared different farming practices and found that NT had the highest C and N storage potential, but the absence of tillage did not reduce NO3 leaching. Cover crop destruction and decomposition during autumn and winter increased the soil mineral N in this system. This was in accordance with Himanshu et al. (2019) who used a hydrological model in an Indian watershed and found higher nutrient losses, but lower sediment concentrations under NT.

Soil Type In this study, the only significant difference between soil moisture values was found between NT-S and NT-C ($P = 0.0224$), with the mean soil moisture values highest at NT-S (20.3%) followed by CT-C (20.0%), and the lowest mean soil moisture level was at CT-S (15.4%, significantly lower than the three other fields: $P < 0.001$). An important difference between the NT and the CT fields was that the soil moisture distribution in the soil profile was different (figure 5) as the NT-C field did not show the same declining trend with depth as in the rest of the fields, while NT-S showed the greatest soil moisture gradient resulting from much higher moisture content in the topsoil.

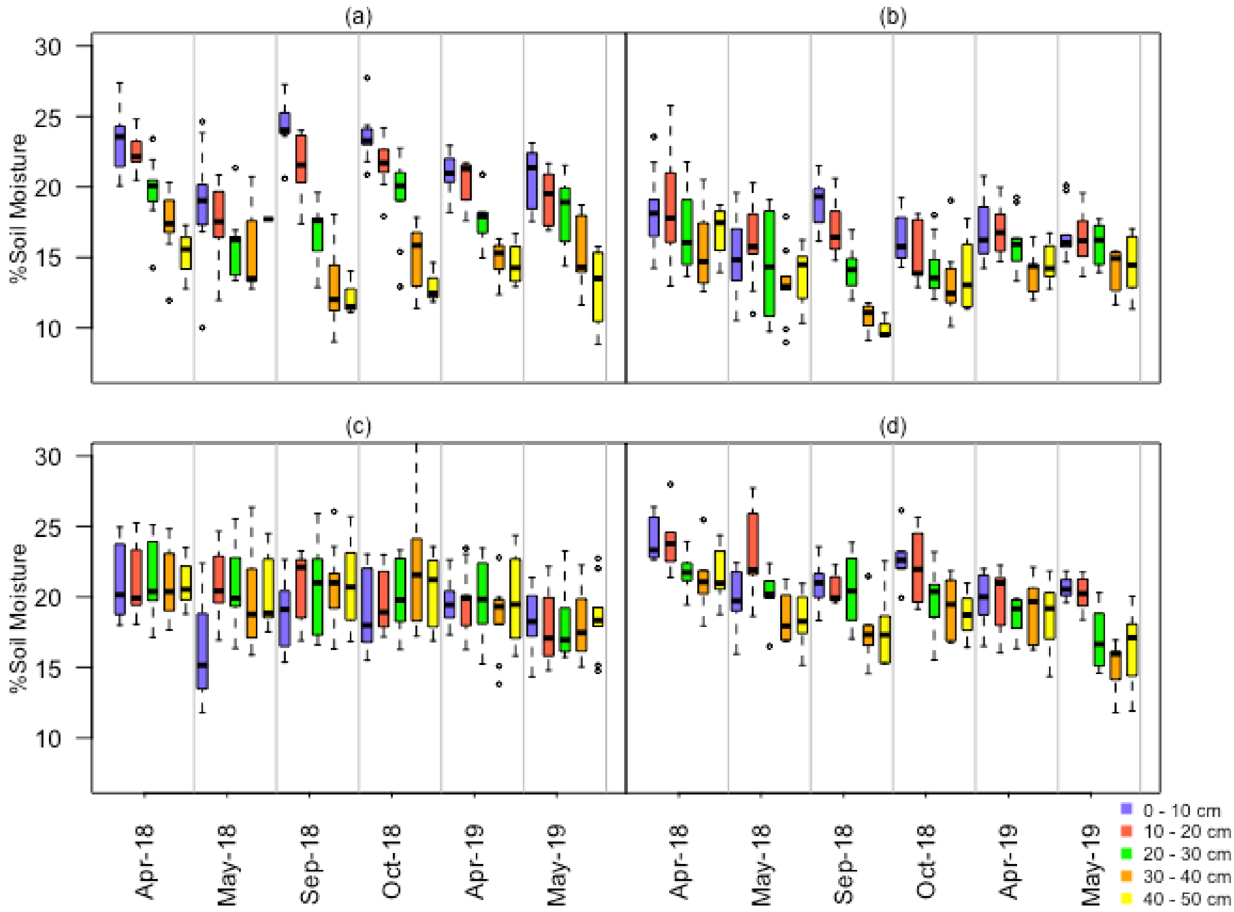

Figure 5. Soil moisture levels at (a) NT-S, (b) CT-S, (c) NT-C, and (d) CT-C at different depths (represented by the different colours; key provided below) sampled from Spring 2018 to Spring 2019 showing mean values and 75% confidence intervals.

There was a significant difference in bulk density between fields ($P < 0.05$), but not for the different sampling depths (surface and subsurface) nested within the fields ($P > 0.05$). Although there was no significant difference between the practices ($P > 0.05$), there was a significant difference between the different soil types nested within the different practices ($P < 0.05$). The lowest mean bulk density was found in the topsoil of NT-S (mean: 1.04 g/cm3), that might partly be explained by the elevated levels of topsoil SOM in this field (figure 2) compared to the three other fields (Behrends Kraemer et al., 2019). However, the variation was very high within this field and the subsoil bulk density was markedly higher (1.31 g/cm3) meaning that the soil is more compacted at greater depths in this field. Both the highest and the lowest SOM levels were found in the Cotswold Brash fields (figures 2 and 3a). There was a large variation between the two lime-rich loamy fields with higher compaction in the NT field than the one of CT (table 1).

The suitability of NT is highly related to soil type and soil characteristics such as drainage and structural properties (Soane et al. 2012). Cannell et al. (1978) devised a three-tier classification system for UK soil types based on their suitability to NT; Calcareous self-mulching clays derived from limestone or chalk were considered to be one of the most suitable soil types, while undrained clay soils with poor structure were found to be unsuitable for this practice. Therefore, Alskaf et al. (2020) reported that in their study low disturbance farmers (reduced tillage) were forced to plough their heavy clay soils during wet years to help drainage. The potential challenges associated with water logging under low disturbance practices in a wet climate clearly showed the importance of climatic factors for the suitability of different farming practices, in addition to soil types. The higher bulk density found in NT-C (table 1) could be a result of a combination of the soil type, poor structure and low drainage. The lime-rich loamy fields in this study cracked during the dry summer months (especially during 2018 when the region underwent severe water deficit), which has been suggested as another factor that can degrade the soil structure by reducing the aggregate stability (Behrends Kraemer et al. 2019) and therefore increase the risk of compaction.

Chi et al. (2016) found higher correlation between soil moisture and C under NT than CT and suggested that soil disturbance could be a possible explanation, where disturbance under CT break the C water connections. The highest correlation between SOM content (directly related to the C content) and soil moisture in this study was found in NT-S, however, overall these findings contradict the findings of Chi et al. (2016) as the soil type had a more significant influence than farming practice, with similarly high correlations between SOM and soil moisture in the Cotswold Brash field under CT.

The highest mean NO3 level was found at CT-S (14.3 mg/L) that was significantly higher than all the three other fields ($P < 0.01$), the lowest was NT-S (10.8 mg/L) and the two lime-rich loamy fields had very similar concentrations (NT-C = 11.1 mg/L, CT-C = 11.0 mg/L) (figure 3). There were no significant differences between the latter three. The NH3 content was significantly higher ($P < 0.05$) at CT-S (mean concentration of 3.79 mg/L) than the three other fields. The lowest mean level was found at NT-C (2.51 mg/L).

For the SOM and NO3, the lime-rich loamy fields under CT and NT had similar concentrations and patterns (figure 3). There was an overall positive correlation between SOM and soil NO3, but this correlation was not evident when comparing between fields as there was an inverse relationship between the SOM and NO3 levels, meaning that the fields with the highest SOM levels also had the lowest NO3 levels. In contrast, the PO43- concentrations were similar for the two Cotswold Brash fields and there was a greater variation between the two lime-rich loamy fields (figure 3). One possible explanation was the differences in pH between these fields, as the NT field had much lower pH (6.9) than the CT field (8.1), while the Cotswold Brash fields both had pH value of 8.1. Soil P cycles in various forms, both organic and inorganic, and PO4 is the plant available form, and the soil pH is one of the determining factors for P availability. The lower pH of the NT lime-rich loamy field was more suited for P availability than the more alkaline pH found in the three other fields due to fixation by aluminium, calcium or iron, partly explaining the differences in PO43- levels between the two lime-rich loamy fields.

The NO3 form of N is crucial for plant growth but can cause pollution if leaching to ground- or surface-waters. The degree of NO3 leaching varies with soil type, geomorphology and groundwater level (affecting oxygen concentrations and therefore denitrification losses), land use (affecting organic C contents and therefore denitrification), precipitation surplus (oxygen levels) and root depth (decreasing root depths increase the risk of leaching) (Velthof et al. 2007). Additionally, fertiliser applications (excess amounts are more likely to leach) and the retentive properties of the soil that are depending on soil texture, SOM and cation exchange capacity (Gaines and Gaines 1994) can influence NO3 leaching.

The infiltration capacity of the soil depends on the porosity, which differs from one soil to another; loose sandy soils are associated with high infiltration rates, while heavy clay or loam soils often have smaller infiltration capacities. The lowest infiltration rates were found at NT-C (table 1), but readings were challenging during the spring because of crack formations in the soil (in both NT-C and CT-C). Low infiltration rates can contribute to increased NO3 leaching as increased surface runoff is an important contributor to water pollution by NO3. Erosion is however a lesser problem, in contrast to P losses, as N is more soluble than P and therefore more often transported with water than with particles.

Gaines and Gaines (1994) found that soils with higher levels of clay, silt and SOM retained more NO3 than more sandy soils. Often the amount of N added by the farmers exceeds the amount that is taken up and removed by harvesting of crops and grazing by animals, leading to a N surplus that can be immobilized by the soil or lost to the environment through leaching or emissions (Galloway et al. 2003; Sutton et al. 2011). Velthof et al. (2007) found that parameters that increased the risk of N surface runoff were the weather conditions (heavy precipitation, snowmelt etc.), soil conditions (infiltration rates), fertilizer inputs, type of vegetation and length of growing season, type of tillage and slope steepness. The steepest fields in this study were the Cotswold Brash fields, but the rapid infiltration rates at these two fields were likely to prevent most of the NO3 surface runoff. However, NO3 leaching was more likely in these fields than on the poorly drained wet soils, but fields of high SOM content (NT-S) increases denitrification and can therefore decrease NO3 leaching.

Significant NH3 losses in the form of volatilization and gaseous emission is an important contributor to the overall N losses and occur especially after application of animal manure or mineral fertilizer applications to agricultural fields (Oenema et al. 2007). The elevated concentrations of NH3 in NT-C and CT-S measured in May 2019 (figure 3c) was most likely the result of sheep grazing in these fields in the Spring of that year.

In-Field Variations PCA analysis determined that the strongest quality representation related to sampling depth (figure 6), contributing more than 30% of the first dimension of explained variance. The correlogram showed a strong negative correlation with increasing sampling depth and SOM, soil moisture, NO3 and PO43-, although there is no correlation between NH3 and soil depth. The differences with soil depth were significant in all four fields for SOM ($P = < 0.001$), NO3 ($P < 0.001$) and PO43- ($P < 0.01$), while significant for soil moisture in all fields apart from NT-C for ($P = < 0.001$) and only significant for NH3 in NT-S and CT-C ($P < 0.01$). There were significant differences in SOM concentrations with time for all fields apart from CT-C, where there was an increasing trend in the Cotswold Brash fields (particularly for NT-S), while the values in NT-C experienced very little change over the sampling period. All fields apart from CT-S had significant changes in soil moisture with time ($P < 0.01$) with a declining trend particularly in the lime-rich loamy fields, probably as a result of the unusually dry weather in this part of the UK during the monitoring period that led to a serious water deficit. There were significant differences in NO3 concentrations with time within all the fields ($P < 0.05$), with an increasing trend for the CT fields, while declining in NT-S. A similar increasing trend was found for NH3 with significant differences in concentrations with time for all fields ($P < 0.001$), while the changes in PO43- with time were significant ($P < 0.05$) for all fields apart from NT-S, increasing for the Cotswold Brash fields and slightly decreasing for CT-S.

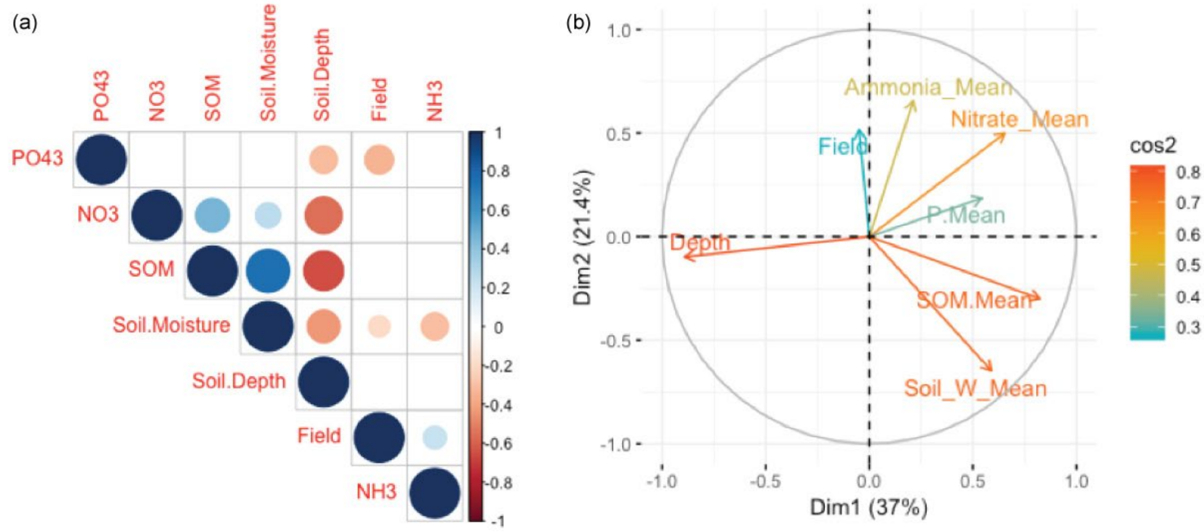

Figure 6. Results of the correlations between Phosphate (PO43-), Nitrate (NO3), Ammonia (NH3), soil organic matter (SOM), soil moisture content, soil depth and the four different fields (field): (a) combined correlogram and significance test (insignificant values are left blank) and (b) the Principle Component Analysis (PCA) chart showing the direction and strength of correlations based on the two major principal components (Dim1 and Dim2).

Vertical Variability The correlation between SOM, soil moisture, NO3 and PO43- with depth demonstrated by this study (figure 6) demonstrates the importance of considering sampling depth when collecting soil samples, and also when reporting the data. Figure 7 illustrates how NO3 and PO43- concentrations vary as you move deeper in the soil in the two Cotswold Brash fields (NT-S and CT-S), with a reduction in concentration as you move away from the soil surface. Our results demonstrate that samples should be collected from several depths, or as a mixed sample from the soil profile, as the distribution of nutrients varied with depth and this concentration varied between sites and temporally; for example in CT-S the highest concentrations of NO3 were at 10 to 20 cm depth during the 2018 sampling but at 0 to 10 cm depth in Spring 2019 (figure 7b), whereas the highest concentrations in NT-S were consistently found at 0 to 10 cm depth (figure 7a).

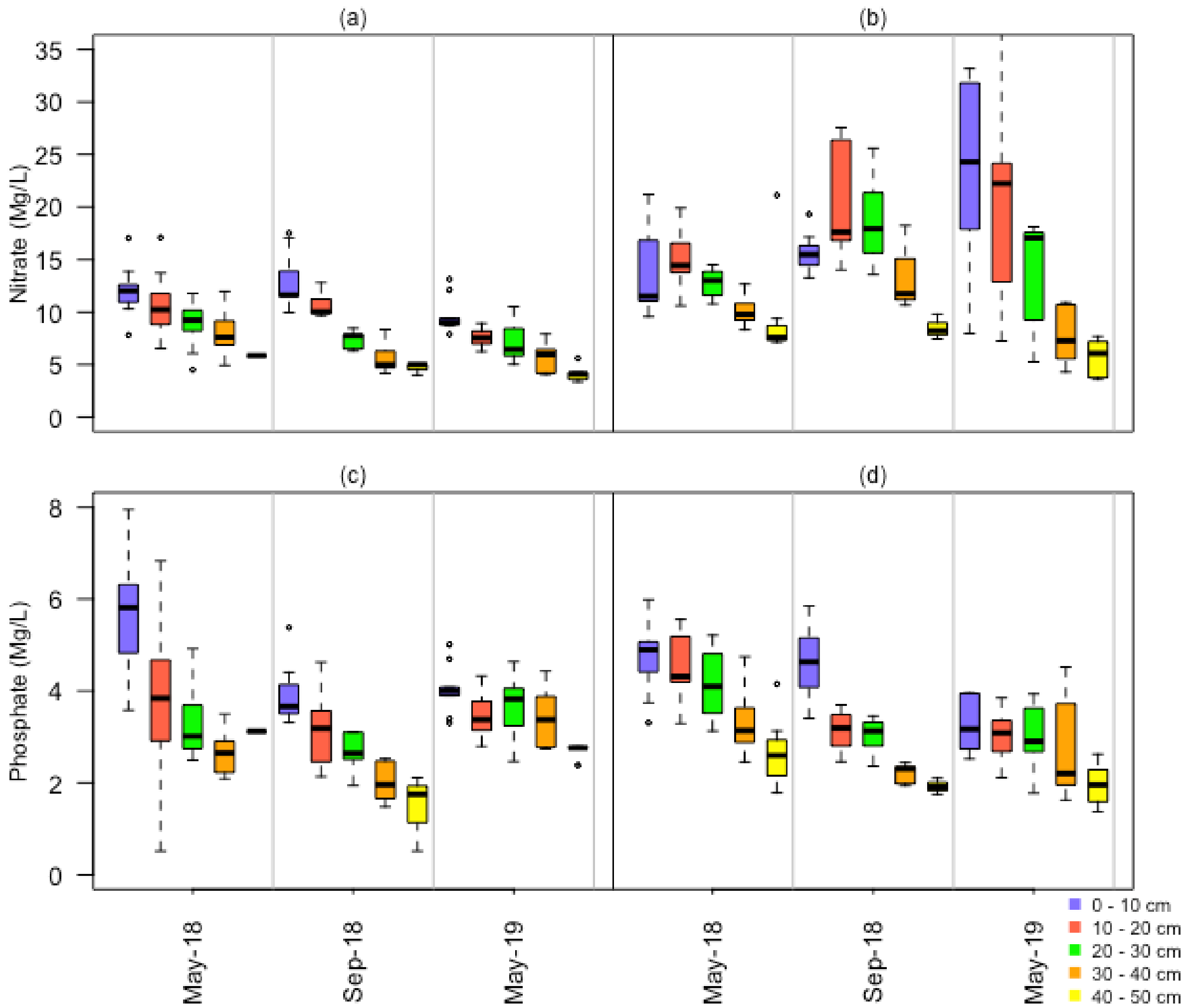

Figure 7. Soil Nitrate (NO3) concentrations in (a) NT-S and (b) CT-S and soil Phosphate (PO43-) concentrations at (c) NT-S and (d) CT-S showing mean values and 75% confidence intervals at different sampling depths (represented by the different colours; key provided below).

Spatial Variability The second strongest quality representation in the PCA related to SOM levels, followed by NO3, while NH3 and soil moisture had the highest contributions to the second dimension (Dim2) (figure 6). The highest variance within fields of both SOM (NT-S = 3.71, CT-S = 2.68) and NH3 (CT-S = 1.51 and NT-S = 1.28) were found in the two Cotswold Brash fields, while the highest NO3 variance was found within the lime-rich loamy fields (NT-C = 4.88 and CT-C = 3.57). There were no such trends with soil type for the within field variation of soil moisture or PO43-, but the largest heterogeneity was found within NT-C for both soil moisture (4.47) and PO43- (12.86).

The findings of this study demonstrate the importance of considering spatial sampling intervals when collecting soil samples, and the significance of reporting on the sampling depth and also spatial variability across fields. Figure 8 demonstrates the variability in NO3 concentrations across the four fields, there were a range of concentrations measured depending on the spatial position in each field, with those under CT having the greatest variance between sampling points (figures 8b and 8d). This highlights that one sampling point per field was not sufficient to determine the situation across a whole field, let alone over multiple fields that have different soil types, composition and management history. The number of samples required to accurately represent the area depends on the soil type, field size and the variable that is being measured. In accordance with other studies (Oorts et al. 2006; Hazarika et al. 2009; Ulrich et al. 2006) our results show that there was spatial variability across the fields for all of the variables that we monitored, but these were distributed differently dependent upon both soil type and farming practice, showing the absolute necessity of designing sampling regimes that were collecting soil from several depths and field locations. Soil analysis based on only one depth and one sampling location, as is often the case for the analysis carried out for farmers themselves (which they use to inform their management decisions), is problematic as it is revealing only a limited part of the in-field complexity and might give an incorrect picture of the field conditions. Knowledge about the soil heterogeneity of a field is crucial to determine the best location for sampling points, and at what spatial interval they should be collected.

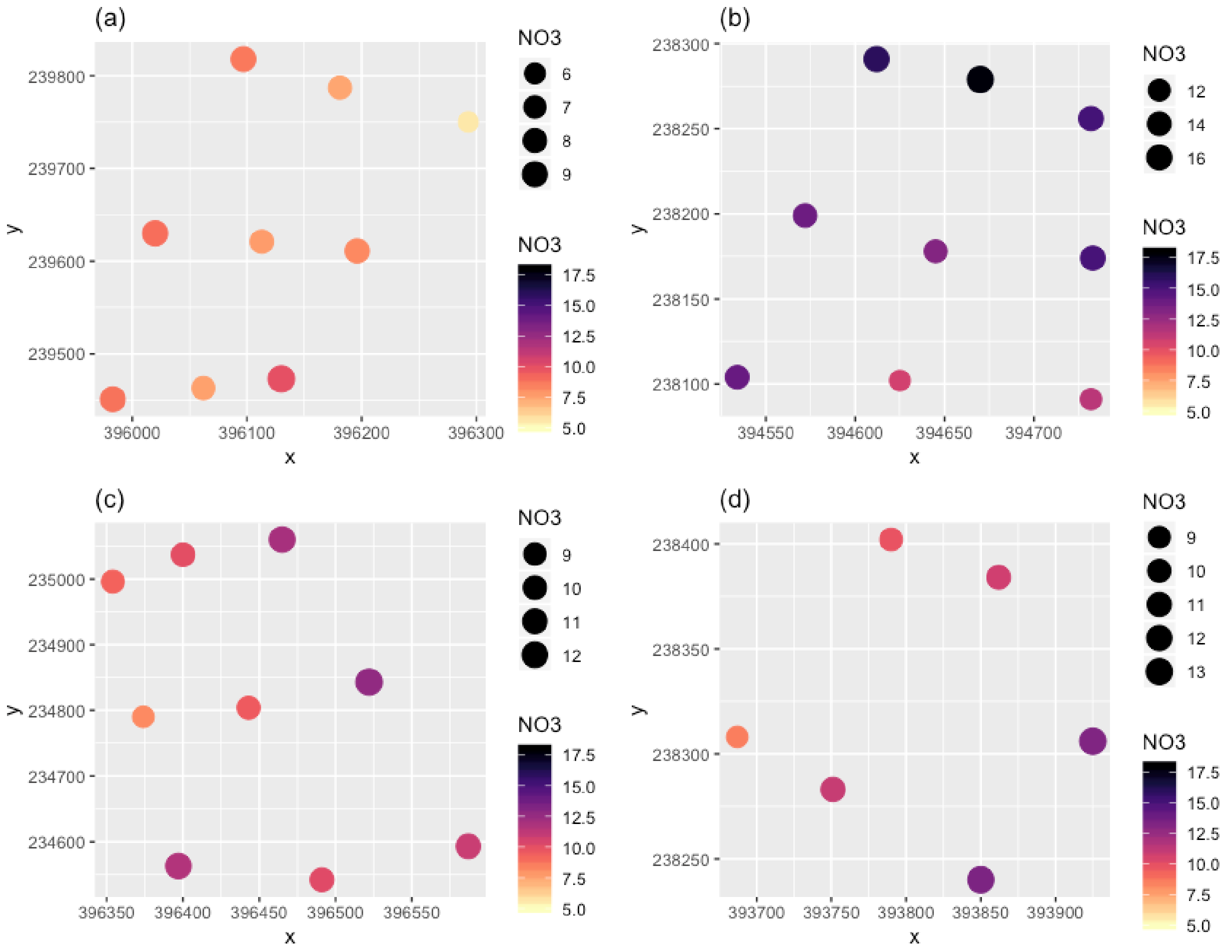

Figure 8. Spatial plot of field sampling locations illustrating variations in the mean values of Nitrate (NO3 in Mg/L) concentrations across the four fields: (a) NT-S (variance of 1.47), (b) CT-S (variance of 4.88), (c) NT-C (variance of 2.06) and (d) CT-C (variance of 3.57). The colour scale shows the range of Nitrate values in general (to compare between fields), while the size scale specifies the actual range that the field is within.

Summary and Conclusions

This study aimed to assess the impact of NT and CT on soil chemical and physical processes and functions of two different soil types and determine their impact on water related soil functions at a field scale, and to investigate the in-field variability. The effects of NT and CT varied between the soil types and variance was often as high within the fields as between fields of different practice. Interestingly, the variables were often more similar between soil types although there were different farmers operating these fields that were using different farming systems.

Our study reveals the following:

1. The impact of NT on soil nutrients is complex. The increased plant material cover on the soil surface under NT increased the levels of soil PO43- and led to the leakage of plant available PO43- in surface runoff, thereby increasing the levels of P in watercourses in close proximity to NT fields. However, the higher SOM and soil moisture levels under NT can lead to higher denitrification rates and therefore reducing soil NO3. There were no notable trends found in NH3 concentrations between NT and CT.
2. The effect of NT on the SOM levels in this study are dependent on soil type, with higher concentrations in the Cotswold Brash field, indicating that there could be higher benefit in implementing NT on this type of coarse, free-draining, weaker-structured soil than the finer, low permeability soils with a stronger structure.
3. The importance of including soils of different characteristics, texture and mineralogy in the assessment of farming systems; highlighting the risk of applying 'catch-all' indicators and recommendations across soil types (Behrends Kraemer et al. 2019).
4. That consideration of spatial variability within fields, both horizontally and vertically, needs to be made when designing the sampling regime for monitoring. Farmer knowledge about the in-field soil conditions and heterogeneity could be particularly useful for this.

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7 Paper III

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The role of farmers' social networks in the implementation of no-till farming practices

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ABSTRACT

This paper draws on network science and uses a Social Network Analysis to improve our understanding of how the implementation of no-till in England is influenced by farmers' social networks. No-till is a low disturbance farming practice with potential to benefit soil health, the aquatic environment and farm economy, but is currently only implemented at a small scale in Europe. Interpersonal networks are important for farmers and influence farmer learning and decision-making and farmers often view each other as their main source of information. In this study, the social networks of 16 no-till farmers in England were mapped and semi-structured interviews carried out to assess the link between farmer network characteristics and the implementation of no-till in England. We also aimed to improve our understanding of the nature and extent of knowledge exchanged within farmer networks and their spatial and temporal dynamics. Our findings suggest that intermediary farmers had an important role in increasing the information flow and knowledge exchange between the different clusters of the no-till farmer network. These intermediaries were also the biggest influencers as they were often no-till farmers with a high level of experiential knowledge and viewed as important sources of information by other farmers. No-till farmer networks were geographically distributed as the farmers preferred to discuss farming practices with similar minded no-till farmers rather than local conventional farmers who did not understand what they were trying to achieve. Therefore, online communication platforms like social media were important for communication. We question the role of formal extension services in supporting farmers with innovative practices like no-till and suggest that advisors should strive to improve their understanding of these well-developed information networks to enable a more streamlined and efficient information diffusion.

1. Introduction

The Agricultural Innovation Systems (AIS) approach regards innovation as the result of a process of networking and interactive learning amongst a heterogeneous set of actors (Hall et al., 2003; Hall et al., 2004). This framework captures the diverse networks of widely distributed actors and learning pathways that have emerged with a shift toward more demand-driven and market-oriented extension. These networks have been studied from multiple perspectives examining, for example: their interaction with innovation support services in the AIS (Brunori et al., 2013); their role in diffusion (Wu and Zhang, 2013), or translation of innovations through actor networks (Gray and Gibson, 2013; Schneider et al., 2010) the influence of intermediaries and brokers (Cerf et al., 2017; Cvitanovic et al., 2016) and farmers' use of diverse networks seeking information and support (Klerkx and Proctor, 2013). However, less attention has been paid to the network of social relations that surround farmers. Wood et al. (2014) notes “the business of farming embeds farmers in influential relationships with an occupationally diverse array of people”. The structure of these social relations is referred to as social networks and the characteristics of these social networks potentially play a crucial role in the circulation of knowledge within the AIS (Wood et al., 2014; Ramirez, 2013; Cvitanovic et al., 2016).

Social networks have always been an important influence on farmer learning and decision-making (Rogers and Kincaid, 1981). The role of interpersonal networks, forged through discussion groups, farmer to farmer ties, and peer-peer advice networks in facilitating learning has been demonstrated in a number of studies (Isaac et al., 2007; Baumgart-Getz et al., 2012; Schneider et al., 2010; Dolinska and d'Aquino, 2016). Furthermore, meta-analysis has shown that farmer networks (both peer to peer and with other actors) are more influential in sharing information than other more established factors, such as farmers' age and

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farm size (Ramirez, 2013; Baumgart-Getz et al., 2012; Prokopy et al., 2008).

Learning is a social process and as such is bound up in network relations (Lankester, 2013). The nature and extent of learning in networks is multi-faceted, however peer to peer learning is particularly significant, as farmers often view other farmers as their main source of advice: "valuing knowledge delivered by persons instead of roles" (Wood et al., 2014, p. 1). Adoption and diffusion studies in agriculture have consistently shown that one of farmers' most commonly cited sources of information and ideas is other farmers (Oreszczyn et al., 2010; Rogers, 2003). The ability of farmers to innovate and share their own experiential learning, either with peers or more widely, is well documented (Dolinska and d'Aquino, 2016; Munshi, 2004; Morgan, 2011; Ingram, 2015). When individuals develop shared understandings of a problem in this way, this is known as social learning (de Kraker, 2017; Reed et al., 2010). Social learning is influenced by characteristics of the network such as the degree to which actors are connected to others via networks in the knowledge system (Bandura, 1977), while the strength of social ties between network actors influences attitudes and awareness (De Lange et al., 2004), and the uptake of new technologies (Wood et al., 2014; Ramirez, 2013).

Theoretical understanding, together with empirical evidence, shows that social networks can accelerate innovation and cooperation (Lubell et al., 2014; Wu and Zhang, 2013). Multiple studies demonstrate, for example, the role of social ties in agricultural knowledge exchange in promoting or seeding sustainable farming practices (Oerlemans and Assouline, 2004; Cadger et al., 2016; Isaac, 2012). This learning and innovation in social networks is particularly important in the transition toward new agricultural systems such as organic, agro-ecological, and conservation agriculture. These systems are characterized both by the need to develop situated and experiential knowledge (Leeuwis and Van den Ban, 2004), and to share this knowledge in the absence of support from conventional advice systems. According to Klerkx et al. (2010) the influence of individuals in innovation networks are important contributors to socio-technical change. The ability of each actor in a network to take action and make a difference, the actors' 'innovation agency' (Giddens, 1984), relates to the resources and competence that an individual has that can contribute to innovation, with knowledge and skills highlighted as particularly important in the context of successfully implementing new farming practices.

No-till (NT) is one such knowledge intensive system which is emerging as a relatively new practice, adopted on about 157 million hectares globally[1] (Kassam et al., 2015). Scholars, in trying to understand what determines the implementation of new tillage systems (zero, reduced, conservation), tend to take an adoption perspective seeking explanatory factors for farmer uptake. Systematic reviews, however, have revealed that there are no universally applicable factors that determine adoption of new tillage practices (Knowler and Bradshaw, 2007) or soil conservation more widely (Wauters and Mathijs, 2014). Instead, the significance of social capital (described as the interconnectedness amongst individuals) and of farmers acting as innovators and sharing knowledge on new tillage systems in social networks was identified as important for farmer decision-making (Knowler and Bradshaw, 2007; Ingram, 2010; Schneider et al., 2012; Bellotti and Rochecouste, 2014). This suggests, in accordance with AIS perspectives, that understanding the dynamics and relations of social networks is a more useful way of revealing the active and creative role of farmers and other actors in generating innovation in the context of tillage systems.

While the role of social networks in NT implementation is known anecdotally to be important, there is a lack of research that seeks to identify the nature and role of these social networks. Using what Lubell et al. (2014) calls "network science" offers systematic methods that can help elucidate social networks more explicitly. Using these methods to understand the structure and function of social networks will not only help to reveal the role of farmers and other actors in NT innovation but also identify leverage points in agricultural advisory systems (Bourne et al., 2017). This is important as NT is a low disturbance farming practice that has potential to improve soil health (Bertrand et al., 2015; Crotty et al., 2016), reduce soil degradation by erosion (Skaalsveen et al., 2019; Lundekvam, 2007), improve water quality (Schoumans et al., 2014; Mhazo et al., 2016), as well as offer economic benefits to farmers (Lahmar, 2010; Kassam et al., 2012). It is, however, currently only implemented at a small scale in Europe (Schneider et al., 2012; Kassam et al., 2015).

This paper, therefore, aims to better understand how the implementation of NT in England is influenced by farmers' social networks. It uses a Social Network Analysis (SNA) approach to map the connections of the social network of a sample of NT farmers in England and "opens a window into the mechanisms behind the dynamics of social interactions" (Reychav et al., 2016, p. 444). Alongside the SNA, semi-structured interviews provide an in-depth analysis of the interconnectedness of targeted NT farmers. Specifically, the paper addresses the following research questions:

- Is there a link between farmer network characteristics and implementation of NT? What are the structural and functional attributes (according to SNA methodology) of networks of farmers who have adopted NT farming? Who are central to these networks and who are the influencers?
- What are the temporal and spatial dynamics of farmer networks in relation to NT?
- What is the nature and extent of knowledge exchanged in social networks?

2. Characterising social networks

2.1. Social networks and learning for NT

Social networks are particularly important for new practices where conventional advice systems are inadequate. Farmers look for alternative support and substitute formal knowledge with their own informal sources from within the farming community (Isaac et al., 2007; Ingram, 2010; Šūmane et al., 2018). In this case, information diffusion then becomes highly dependent on the relationships and interactions between farmers (Wu and Zhang, 2013).

A transition to a complex system like NT demands a higher standard of overall management compared to ploughing, often gained through experimentation (Milestad et al., 2010a; Ingram, 2010), learning from others (Brunori et al., 2013; Maddison, 2007), problem solving and building up of experiential knowledge (Ingram, 2010; Samiee and Rezaei-Moghaddam, 2017; Baars, 2010). In similar system changes which require attention to detail, for example organic farming, the importance of knowledge building and social learning in networks in the absence of formal information sources has been demonstrated (Padel, 2001; Morgan, 2011). Similarly for agroecology in Canada, where farmers were marginalized with little direct access to institutional or governmental support, emerging networks were described by Laforge and McLachlan (2018, p. 266) as a "mycorrhizal network of hidden underground ways that connected farmers together through virtual or online communities" that enabled new farmers to gain knowledge.

In such transitions farmers rely particularly on experience-based knowledge as it has practical, personal and local relevance and is accumulated over long periods of time by doing, experimenting and observing (Šūmane et al., 2018). Through these processes farmers learn to recognise what works on their farm and come to understand their soil, plant and farming system (Ingram, 2010). They change their behaviour over time as a result of observable outcomes on the farm and are encouraged to experiment further by the experience of success (Lubell

[1] Data from 2013 published by FAO

et al., 2014; Milestad et al., 2010b). Experiential learning is a constant process that happens not only at the individual level but also at the interpersonal level as practical experiences are shared and joint problem solving undertaken, in accordance with social learning concepts (Laforge and McLachlan, 2018; Oreszczyn et al., 2010; Milestad et al., 2010b; Lubell et al., 2014). Ingram (2010) showed how individual farmers learn at the farm level through experimentation and adaptation, used a variety of networking devices to take this learning and validate and reflect on it by interacting with others with the same experiences. In doing this the individual activity of on-farm learning is accompanied and enhanced by a process of social learning. Networks extend other actors and information from several sources is also drawn in to support management decisions (Bellotti and Rochecouste, 2014).

3. Methodology and methods

3.1. SNA components

In this study the social networks were measured using a SNA, which is a body of research methods to represent the structure of social networks including network matrices, diagrams and mathematical measures (Bourne et al., 2017; Otte and Rousseau, 2002; Haythornthwaite, 1996), with a set of procedures built on principles from graph theory for analysing the presence, direction and strength of connections between actors (Scott, 1988). The methodology entailed SNA to assess the characteristics of the ego-networks (e.g. identify frequency of interaction, homophily, formality and influence of different members) of each farmer in the study, and the links between them.

A social network is a set of connections amongst people with various social relationships where information and other social processes flow. Actors within networks are referred to as “nodes” and their relationships seen as “links” or connections (Borgatti and Halgin, 2011; Wasserman and Faust, 1994). The connections, distribution and segmentation of nodes are important aspects of social networks, characterising aspects such as the reciprocity, centrality and cohesion respectively (Ramirez, 2013). Centrality is an important factor in social networks with central actors being strongly influential (Scott, 1988) and hold critical resources in the network (Reychav et al., 2016). The information that is flowing within networks often depends on key actors that can be both negative and positive to adaption and act as “communication bottlenecks” or “community bridges”. Bridges, also known as knowledge brokers, are important for new information and innovation as they contribute to increased information flow by transforming explicit knowledge from actors outside the group to tacit knowledge within the group (Bourne et al., 2017). The type of actors within a social network is also important for the information flow as networks with a high degree of homophily, assessed by comparing the number of links between similar actors to the number of links between different actors, can limit knowledge diffusion as there are limited ties to actors outside the network and therefore little access to information that does not exist in a closed circle of friends, family or neighbourhood. Actors of networks with high homophily mostly have ties to people who are similar to themselves (e.g. mostly farmer-to-farmer interaction).

Social networks enhance adoption of new technology by increasing the information[2] flow and knowledge[3] exchange due to the interaction between actors (Ramirez, 2013). A high density of ties (connections) in a network means a high level of interaction between actors which increases the potential for information distribution, resilience and social memory of the group. Ramirez (2013) suggests three forms of social collaboration amongst farmers in social networks: kinship relations (family), land owner-tenant relations (work) and affiliations (social associations). In-family networks are in this paper understood as the interactions between family members cooperating within the farming business.

Boundaries are an important part of the SNA as some structural features of networks can only be interpreted correctly when the information is gathered from all the actors in the network (Marsden, 1990). Farmer network boundaries can be difficult to determine in an agricultural context and involve a large number of actors (Bourne et al., 2017), making it necessary to focus on personal networks where all relationships of one actor are registered, often referred to as ego-networks (Bourne et al., 2017; Baird et al., 2016; Marsden, 1990).

3.2. Recruitment and data collection

Farmers were identified through Twitter, by searching for NT farmers on the internet and from snowballing from already established contacts. All identified NT farmers were approached by email or Twitter with a request to participate in an interview and a SNA. As there is still a relatively low number of NT farmers in England, only covering around 4% of the total cultivated area at the last estimate (Defra, 2010), finding and approaching as many as possible was the only way to get a satisfactory number of individuals. Eighteen farmers were recruited for the interview and 16 of them participated in the SNA. Most of the farmers in this study were five years or less into the practice, but several had a transition period of reduced or minimal tillage before implementing NT. The interviews were conducted between August and November 2018, and lasted between 45 and 60 min. The farmer interviews were digitally recorded and transcribed verbatim to a Word file.

3.3. Social network analysis method

The network data was gathered by asking participants about the individuals in their social network. The researcher directed the participant to indicate who they discuss their NT farming practices with, with responses recorded on a table (see Appendix). This inevitably resulted in respondents mentioning the individuals in their network by name, therefore any identifying details were removed from the table prior to analysis. Additionally, respondents were asked to provide information about (i) each persons' ‘occupation or their relationship to this person (e.g. son, father, wife)’, (ii) whether they had a ‘formal’ or ‘informal’ relationship,[4] (iii) whether the person had implemented NT (if applicable), (iv) how often they would discuss with this person (daily, weekly, monthly or less), (v) their main way of communicating (face to face, telephone, social media, farmer events, forum or other), (vi) how often they would seek each other's advice (daily, weekly, monthly or less), (vii) how influential the person was (score from one to five) and (viii) if they started communicating ‘before’ or ‘after’ they implemented NT. The SNA figures only show farmers within the UK.

The temporal dynamics of networks of farmers in this study was measured in the SNA by assessing the changes in farmers' social networks before and after they implemented NT on their farm. The farmers were asked who they were influenced by before and after NT, and what sources of information they used to learn about NT during implementation and after. Spatial dynamics of farmer networks were determined by the geographical distribution of actors in the SNA before

[2] Information comprises facts, interpretations and projections, while advice implies the recommendation of a particular course of action or the presentation of different alternatives (Garforth et al. 2002).

[3] Peoples understanding of the information turns it into knowledge (Stenmark, 2002).

[4] The terms ‘formal’ and ‘informal’ were in this context left for the farmers to interpret based on their own definition of the words and types of relationships. In relation to information networks, ‘informal’ connections normally refer to peers or community-based sources, while connections to organisations, extension agents etc. are seen as ‘formal’ (Isaac, 2012).

and after NT implementation, and whether they were local, regional, national or global actors of their networks.

Alongside the SNA, a semi structured interview was conducted with each farmer to provide details of each farmer's reason for implementing NT, what sources of information they used to make the transition and where and how they would seek information today, how farmers characterise and evaluate the level of knowledge in their networks and how the networks developed after implementing NT. The nature and extent of knowledge communicated within the social networks of the farmers in this study was assessed by interviewing farmers about their perceived level of knowledge within their farmer networks and amongst the local farmers in their area. The types of actors in their networks (i.e. other farmers, researchers etc.) and the kind of knowledge that was shared (e.g. based on experiential knowledge or research) indicated whether the nature of information that was shared between the actors was tacit or explicit.[5]

Although theoretically we can differentiate information and knowledge, at a farm level the two terms are used interchangeably.

3.4. Data analysis

The SNA was carried out using the online software Polinode where relational data from the NT farmers was uploaded via an Excel template provided online, where all nodes (actors in the social network) and edges (the relationships between them) were specified. The software then generated a network figure of the nodes and edges of the network based on the input from the template, and further analysis was carried out by using different functions and matrices within the software. The SNA collaboration matrix was created by calculating the extent to which actors, based on their occupation (e.g. farmer, advisor, academia), interact with each other. A NT farmers' acquaintance network was built by the same method to assess the degree of connectedness between the 16 respondents in the SNA study. Built-in metrics in the Polinode software were used to calculate the in degree (the number of incoming edges, illustrating the number of times an individual is mentioned by other actors in the SNA), out degree (the number of outgoing edges, illustrating the number of other actors the individual listed in the SNA), the sum of incoming and outgoing edges (total degree) and the network density.

Influencers were identified by the combination of the number of incoming edges and the influence rating (scale from one to five) in the SNA analysis. These are key actors with high importance to knowledge flow because of their central role in the network (Bourne et al., 2017). The definition of intermediaries varies; the extension services were traditionally considered the main intermediary in supporting agricultural innovation by providing knowledge and technology from research to farmers, but this approach has been questioned and the landscape of intermediaries changed as a result of the recognition that innovation requires broad systemic support and interactions between a diverse set of actors (Kilelu et al., 2011). Klerkx and Leeuwis (2008) described innovation intermediaries as organisations or bodies that provide network brokerage, demand articulation and management of innovation processes and function as catalysts of innovation by facilitating the formation and maintenance of innovation networks. While Kilelu et al. (2011) proposed that innovation intermediaries undertake a broader support and management role beyond knowledge brokering by acting as “bridging organisations” that provide access to knowledge, goods, skills and services from a wide range of organisations. In this study, intermediaries were recognised as individuals who connected several other actors and therefore largely increased the overall connectedness of the network, while knowledge brokers were understood as those who connect researchers with the farmers. Early adopters are here defined as a farmer who implemented NT before the practice was common amongst farmers in England (> 10 years ago).

Interview transcripts were analysed using the qualitative analysis software NVivo (version 11.4.3). The thematic analysis was carried out by systematic coding to address all the research questions, meaning that relevant content from the transcriptions was marked and sorted according to the categories outlined that emerged out of the analysis (see Appendix). Once the data was coded it was analysed by comparing the answers and statements from the different farmers and used to explain the results from the SNA.

4. Results

4.1. Network characteristics and implementation of NT

4.1.1. Network characteristics

Drawing on the SNA collaboration matrix, the social networks of the NT farmers in this study mainly comprised other NT farmers. Indeed, 66.7% of the respondents discussed their farming practices with other farmers, and 85.4% of these were NT farmers. The second largest group was agronomists and advisors with 11.3%, followed by researchers (8.5%), representatives of farmer organisations (6.8%), machinery manufacturers (4.0%), suppliers (e.g. seeds) (1.1%) and others (1.7%) (Fig. 1). The network consisted of 177 connections (edges) between the 134 nodes and 32% of these relationships were seen as formal.

The farmers mostly had informal relationships to each other, while they often saw their relations to non-farmer contacts as formal. The key farmer nodes in Fig. 1 were NT farmers who had the largest number of edges coming in (listed as a source of information or discussion by other farmers in the network) and the biggest sized nodes (how influential the other farmers rated them as).

4.1.2. NT farmers' acquaintance network

The NT farmers' acquaintance network shows only the farmers that participated in this study without the rest of their ego-networks (Fig. 3(a)). The connectedness between these NT farmers has been analysed to assess the direct connections between them. The network density of the acquaintance network is 0.071 and is calculated by dividing the actual number of ties by the total possible number of ties (Scott, 1988), meaning that only 7.1% of the possible connections were made (100% would mean that all members would be directly connected with each other). This is a measure of network cohesiveness and shows that the farmers in this study are mostly connected by fellow contacts, and not by direct links to each other. The total average degree of the network is 2.13, which is the number of edges that start from or point to a node.

4.1.3. Information from interpersonal social networks

All the interviewed farmers stressed that the transition to NT was farmer-led and that the most relevant information was delivered by their interpersonal social networks, where the most influential individuals were other NT farmers, as illustrated by one participant: “The only person who can sell a new concept to a farmer is another farmer” (Farmer 14). As Fig. 1 shows, the role of individual experienced NT farmers, both from within and outside England, is important for farmers considering, or wanting to start, implementing NT. In-family networks, especially the interaction between fathers and sons, was also regarded as important for successful NT implementation. This was confirmed by the SNA, which showed strong links and high influence between fathers and sons who were working together. Several of the farmers in this study said that young farmers often had larger social networks than their fathers and these were a source of ideas and inspiration to make changes to their farming systems.

[5] Tacit and explicit knowledge are two different types of knowledge. Explicit knowledge refers to knowledge that is communicated in a formal and systematic language, while tacit knowledge is embedded in action, commitment and involvement in a specific context with a more personal quality (Nonaka, 1994).

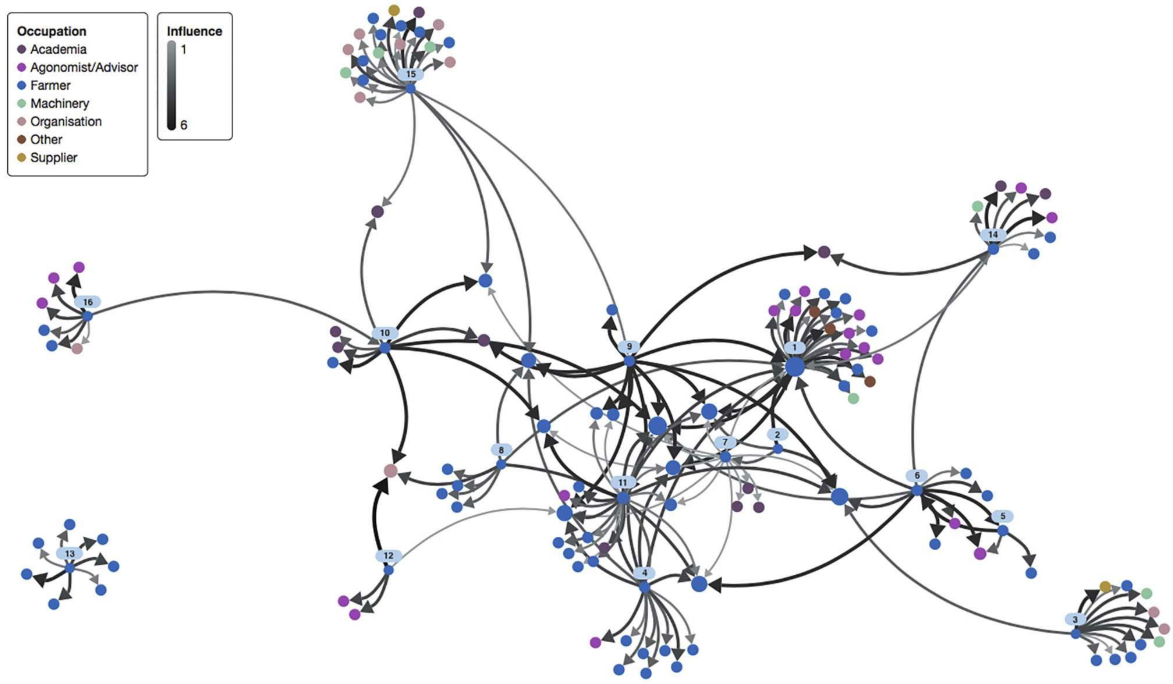

Fig. 1. Social network analysis (SNA) showing the networks of NT farmers revealed in the study.
The nodes of farmers who participated in the study are labelled with numbers from 1 to 16. The colour and thickness of the edges (links) between the nodes (actors) show how influencal other farmers rated them ason a scale from one to five, with darker edges meaning higher influence on their farming decisions. The size of the nodes illustrates how many incoming

It is also the collective understanding of the network that provides some assurance, as this remark referring to the farmer's NT network shows: "The new network gave me the strength and confidence to make a change" (Farmer 4). According to some respondents, farmers' personality traits are also crucial, as the ability to interact and network to find and acquire information was seen as important in becoming a NT farmer, for example: "…they will decide to become NT if they want to because they'll be that type of person who will chat to everyone and get that information. If you're not that way inclined, you are likely not to succeed. It is as simple as that" (Farmer 11).

4.1.4. *Mechanisms for networking*

Most farmers said they preferred to speak to other actors of the network in person, which was underpinned by the preferred methods of communicating with the different actors stated in the SNA (see SNA table in Appendix) showing that 30% of the communication was 'face to face', along with 20% at farmer events. However, as the farmers in the study were spread out geographically, internet platforms were crucial for communication and information flow, with 29% of the interaction carried out on social media (21%) or internet forums (8%) (Fig. 2). Farmers favoured Twitter saying they appreciated the feedback they received, both as a way of questioning or verifying their methods and to hear other people's solutions to problems they encountered. It also allowed them to cross geographical boundaries:

> "That's the good thing about Twitter. It doesn't matter where you're from really" (Farmer 17).

Also all UK based farmers with a NT 'Crosslot' seeding drill were members of the same WhatsApp group which has become a central part of their information network (the group was created by the farmer who started importing the drills to the UK from New Zealand through the family business), enabling them to ask each other questions about NT practices, and the members often viewed each other as key actors in their farming networks.

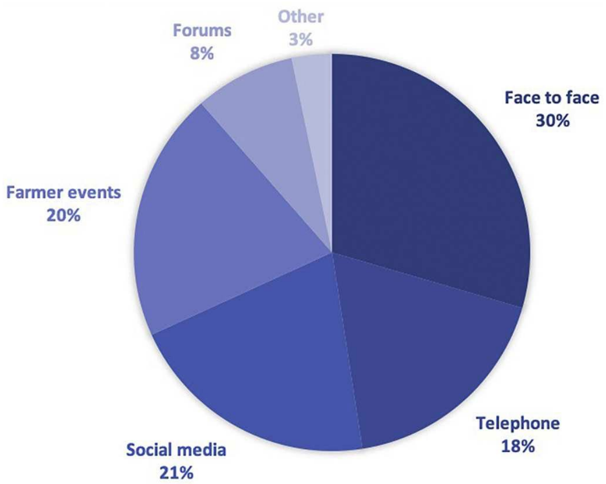

Fig. 2. Forms of communication in the NT farmers' social network.

4.1.5. *Influencers*

As shown in the SNA, some farmers stood out as clear influencers in the network by scoring high on influence rating by other farmers and having a high number of incoming edges. They were often referred to as 'early adopters' of NT and seen to have a high level of experiential knowledge, as well as other characteristics pointed out by the farmers in this study, such as: having shared goals, passionate about what they are doing, having the ability to be innovative and think outside the box, running a good business, or as someone who prompted other farmers to change to NT practices. These influencers have an active social profile through social media. An interesting characteristic of NT networks was that members were highly influenced by international NT farmers with decades of NT experience (notably USA but also New Zealand, Australia, France and Germany), but these farmers were not listed in the SNA as someone they would normally discuss their practices with, so they were seen as sources of inspiration rather than influencers in the network. Some of these connections were made by former Nuffield scholars[6] who expanded their networks by traveling abroad.

Farmers who said that they tried to influence other farmers in their network by giving talks at farmer meetings and conferences were often seen as influential by the other farmers in the SNA:

> "I have gone from one of the people asking questions to one of the people who answers the questions. That's probably how it has changed in the last 7 or 8 years" (Farmer 17).

4.1.6. Intermediaries

Intermediaries, whilst not always early adopters themselves, have an important role in connecting individuals and groups either to each other or to external communities. In doing this, they are also redistributing information to farmers, and are important for knowledge diffusion in the network. Fig. 3 shows the importance of one intermediary (the yellow node) in the network to connect different clusters of the social network. This farmer was not one of the participants in the study, but was identified by seven of the farmers (44% of the participants) as someone they would discuss their NT practices with. Fig. 3(c) shows how the NT farmers' acquaintance network (see Fig. 3(a)) changes when this intermediary farmer is added, tying more of the NT farmers together. This increases the network density from 7.1% to 8.8% and the average total degree from 2.13 to 2.82, which means a 25% increase in the total number of edges in the network. However, there are other individuals who also act as intermediaries in the farmer network, and Fig. 4 shows the same social network, but with the addition of individuals who were identified in the SNA by five or more farmers (> 30% of the participants) (n = 5). By adding these four additional individuals to the network the density increased to 10.7% and the average total degree increased to 4.29, which is by more than 50%.

Some of these intermediaries are also knowledge brokers (Meyer, 2010) as they have links to the science community and see their role as linking formal scientific (explicit) to tacit knowledge and allowing new and different forms of knowledge (e.g. the importance of soil biodiversity and the impact of farming practices on C and N emissions) from outside the farming community to enter the network. One intermediary farmer comments:

> "I see a lot of studies going on that I wish other farmers would be seeing. It doesn't go beyond the paper. The information doesn't go through to the farmers" (Farmer 14).

4.2. The temporal and spatial dynamics of farmer networks in relation to NT

4.2.1. Temporal dynamics

Network dynamics are characterized by changes over time, not only in NT information sources within a network, but also in the reliance placed on it. NT farmers' ego-networks normally expanded after implementing NT, mainly from meeting and talking to other NT farmers. The SNA showed that on average 35% of the connections were made after they implemented NT, although some of the farmers were only a few years into implementing the system. This was due to the necessity of actively seeking information and advice from other NT farmers when transitioning from conventional to NT, as demonstrated by this farmer:

> "There is no manual, as every farm and system is different. People who are just trying to NT without knowing anyone else... I can imagine that that must be quite difficult" (Farmer 6).

The intensity of this increased network interaction largely depends on the time of the year. Some farmers explained that they would talk to other people daily or weekly during critical periods for NT such as drilling or harvest, but only a few times during the rest of the year. However, this is more nuanced, as farmers in this study were found to use networks in different ways, with some farmers already having an established network of NT farmers before implementation and others building their network afterwards. This is illustrated in Fig. 5 which shows two farmers' ego-networks before and after adopting NT. Farmer 4 knew most of his current network before changing practice (four new actors) while Farmer 11 only discussed his farming practices with two people from his network before changing to NT (17 new actors).

For some farmers the role of the agronomist had changed quite drastically as well, from being the main source of information when they were conventional farmers, to being a minor source of information after NT implementation, as the farmers became more knowledgeable about the practice. Despite this, the agronomists were usually rated as highly influential by NT farmers, scoring 4 out of 5 by most farmers in influence score, but this was with respect to fertilisers and pesticide recommendations.

There were also temporal changes to the reliance on social networks associated with the transition farmers go through when they implement NT farming. As farmers built up experiential knowledge about NT, their dependency on other farmers decreased. The common perception by farmers was that farmers were more fixed in their methods, following 'the rules of NT' in the first years after implementation, but that they gradually became more opportunistic as they gained more experience from experimenting on their own farm. Years of building up their own knowledge allowed the farmers to adapt the system more to local farm conditions and rely less on other farmers. Respondents agreed that information about NT has become easier to access in the last few years, both as a result of online availability and a larger community of experienced NT farmers. One of the early adopters explained how he relied on a drill manufacturer for information when he first implemented NT as there were very few other NT farmers. However, he also said that in hindsight, after gaining more experience, he realised that this source of information was unreliable because of limited experience with the practice in England at the time.

4.2.2. Spatial dynamics

The networks of NT farmers in this study differ from the traditional perception of farmers' networks in that, rather than being locally orientated, they extend outside the local area to include national and international members. This is enabled by the use of social media (as shown in 4.1.5) which has in many ways revolutionised the way farmers communicate. Nuffield scholarships and events such as those run by BASE UK, which invite international guest speakers, are helping to build these networks, as described by one farmer:

> "My farming network is all over the place, a lot of social media stuff, so I guess if we start globally; I met a lot of people doing my Nuffield travels and I have kept those connections going so I can find out what happens in agriculture all around the world" (Farmer 1).

Most NT farmers said that their networks included farmers from outside their local area. In Fig. 6 the farmer network was divided into 13 different clusters of the network marked by separate colours, showing a core to the network made up of Communities 1, 2 and 6, while in Fig. 7 all the nodes in Fig. 6 are distributed on a map of

[6] Farmers who have received scholarships from the Nuffield Farming Scholarships Trust. The funding allows 20 farmers each year to research topics of interest, often including international field visits, within farming, food, horticulture or rural industries.

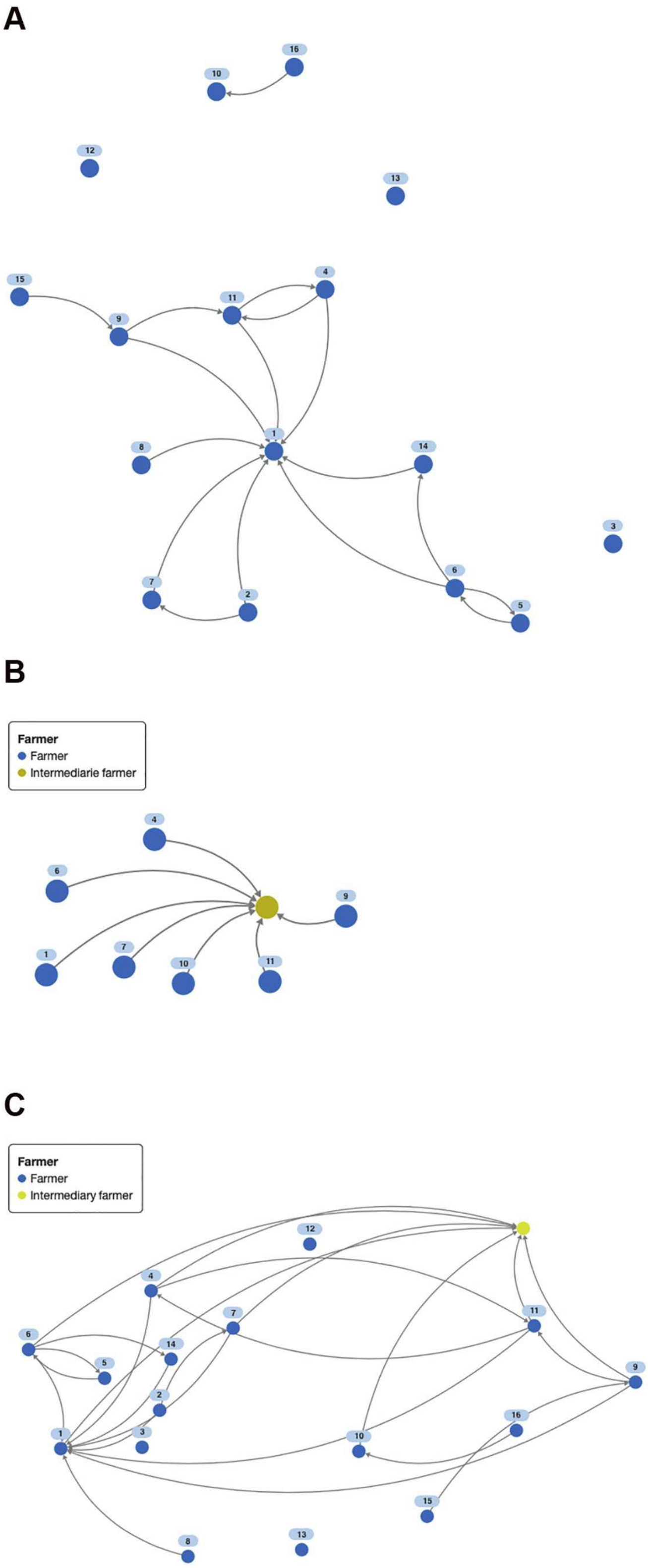

Fig. 3. (a) The NT farmers' acquaintance network illustrating the contact between the NT farmers ($n = 16$), (b) an intermediary farmer from outside the interviewed farmer group who were listed by the highest number of farmers ($n = 7$) in the SNA (yellow node) and (c) The NT farmers acquaintance network including the intermediary farmer (yellow). The average total degree of the network is 2.82 and network density of 0.088 (8.8%). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

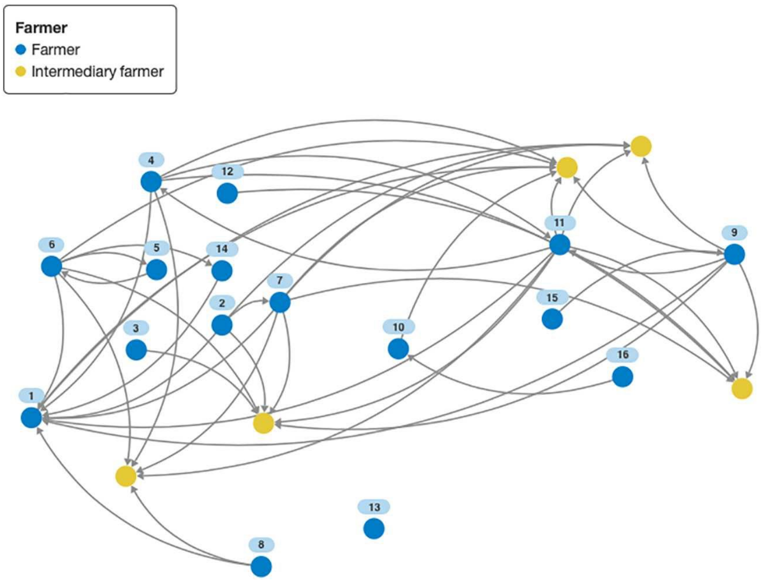

Fig. 4. The contact between the NT farmers (n = 16) (see Fig. 3(a)) including the five farmers (not interviewed) who were mentioned by five or more farmers (> 30% of the farmers). The average total degree of the network is 4.29 and network density of 0.107 (10.7%).

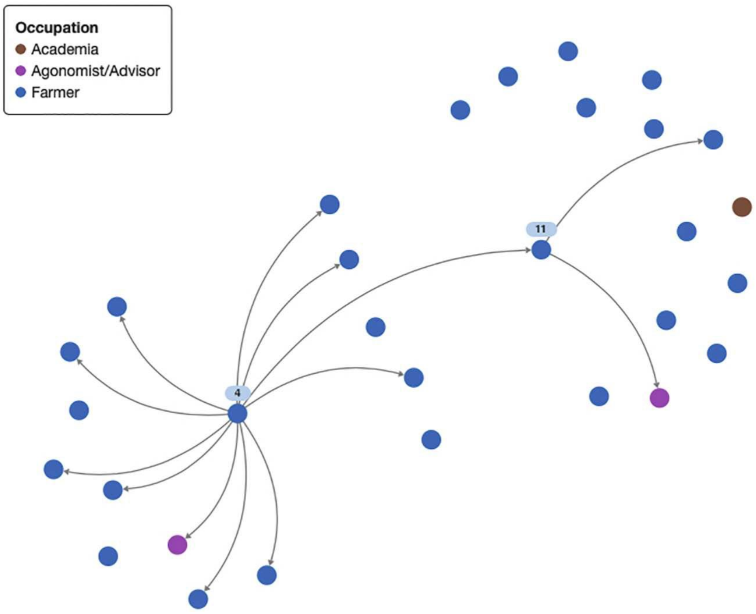

Fig. 5. The ego-networks of Farmer 4 and Farmer 11 showing their networks before (left) and after (right) implementation of NT.

England (with the same colour codes) to show the geographical distribution of each of the individuals within each cluster. There are differences in how spatially scattered the clusters are, but the map clearly shows that NT farmers find their networks outside their local areas. The main reason for this pattern is that there were few NT farmers nearby and overall the level of knowledge about NT amongst local farmers was minimal. The isolation of being a pioneer on NT led the farmers to identify as being different or unconventional:

> "Very few people in the area have gone down the same route as us. We are the black sheep, I'm afraid" (Farmer 18).

Farmers also lacked support from neighbouring farmers who were described as 'nosy' people who were watching over the fence and waiting for them to fail. This is a key reason why they seek assurance and support outside their local community.

4.3. The nature and extent of knowledge communicated by farmer networks

The nature of knowledge about NT exchanged in the farmer networks was tacit rather than explicit. The NT farmer network had a significant role in circulating experiential knowledge between fellow farmers. The emphasis is on sharing experiences and experiments on the farm; joint problem solving when results were poor was an important element in maintaining the NT network. NT is complex with multiple

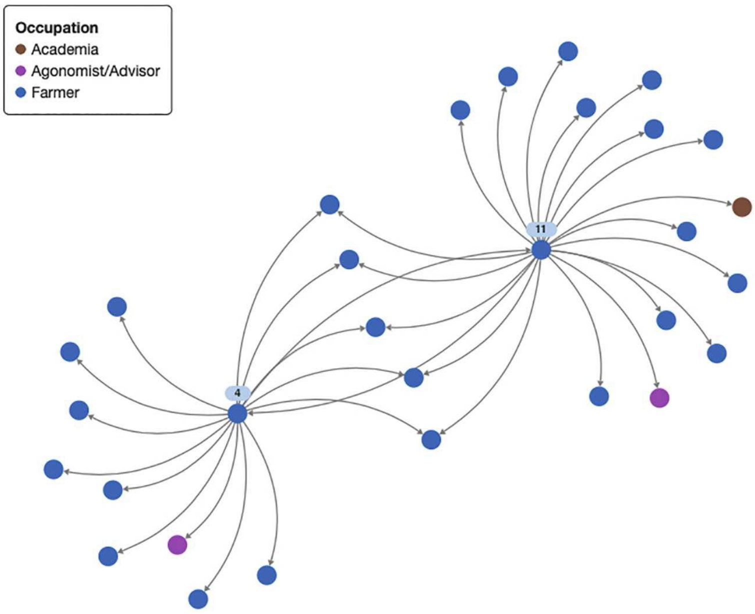

Fig. 5. (*continued*)

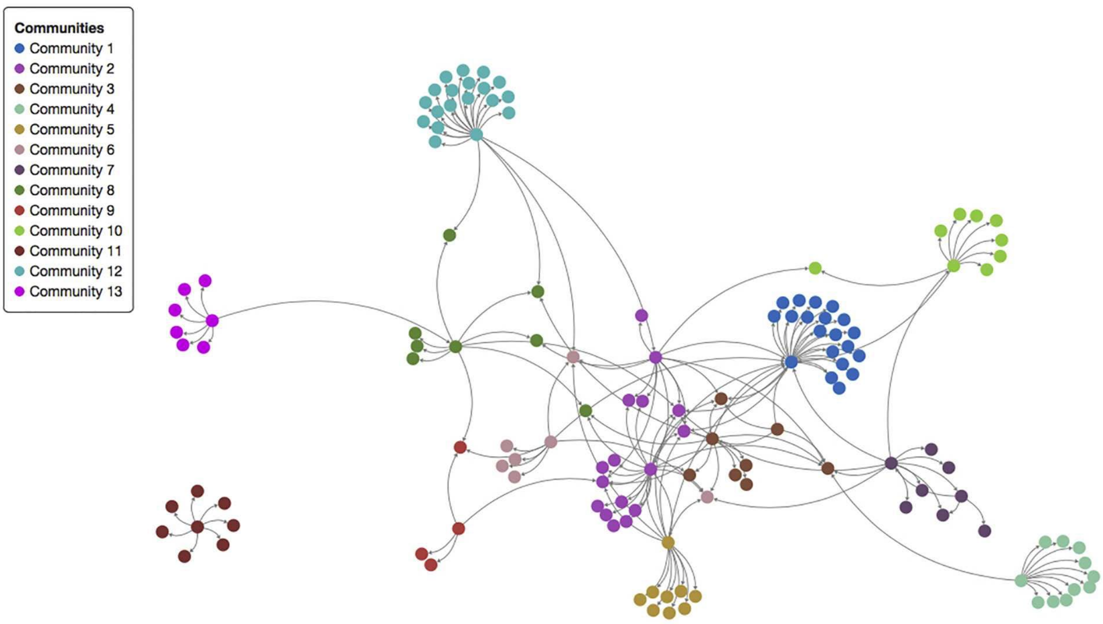

Fig. 6. The 13 different communities of the network generated by the SNA.

variables that affect the outcome (e.g. weather conditions, timing of field operations, different soil types, different rotations, cover crops, crop residues, weeds, pesticides and fertilisers). Acquiring knowledge about all these factors is too challenging for any one individual, and as a farmer you "only have one" go per year and "just a limited number of rotations" (Farmer 13) in a lifetime, so to harvest knowledge from other farmers about different experiences with NT practices is an effective way to enhance learning, as this farmer explained:

> "I would love to have ten goes at it per year, but you only have one. Now we will have to wait another 12 months before we can have another go at it... You spend an awful lot of time thinking about it and a lot less time doing it" (Farmer 13).

This networking and exchange of tacit knowledge between NT farmers compensated for the absence of support or relevant knowledge from more formal sources. Knowledge from the science community was often seen by many as irrelevant or inaccessible, as these remarks demonstrate:

> "I feel disengaged with the science community because they don't see the complexity in a practical day to day system" (Farmer 12).

> "Farmer to farmer learning is a quite powerful tool. There is a whole lot of science paperwork out there, but it is on a shelf somewhere"

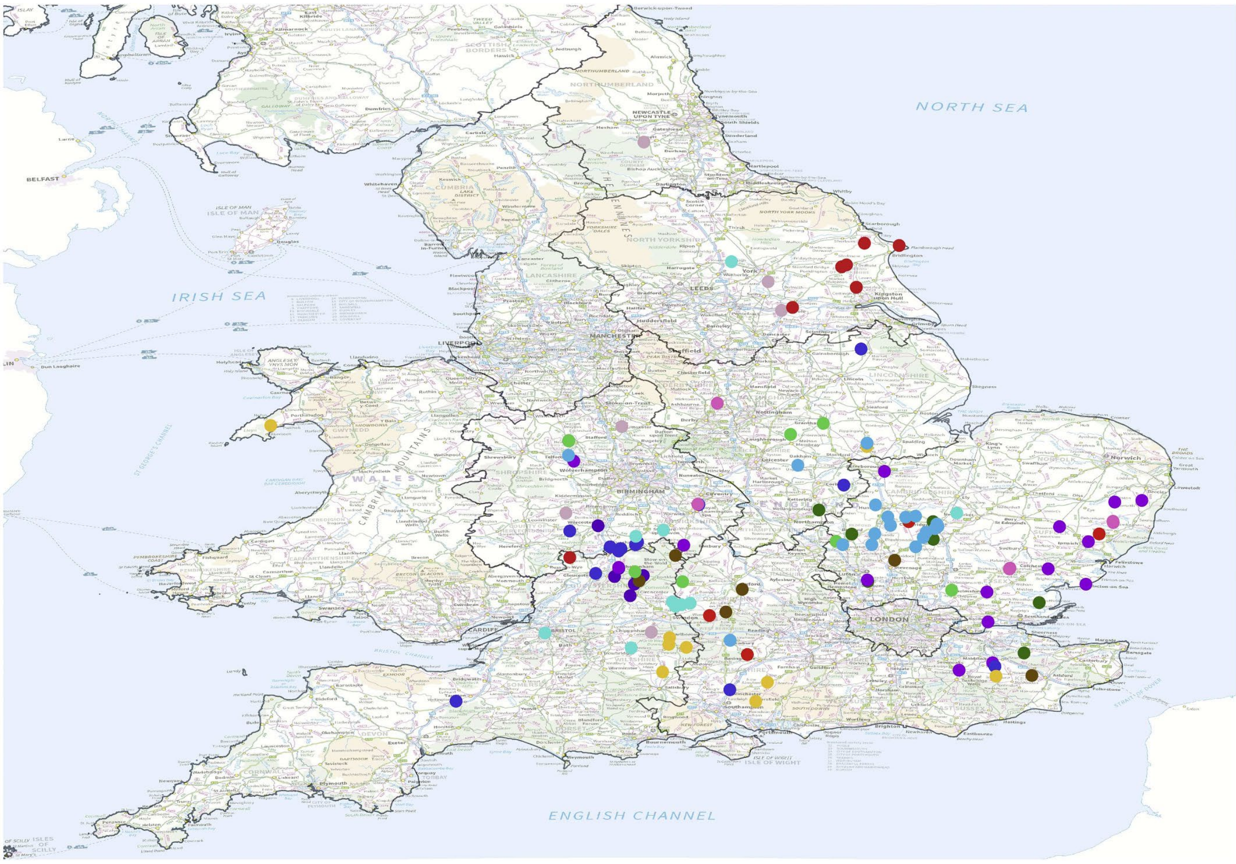

Fig. 7. A map showing how the 13 communities of the SNA (see Fig. 6) are distributed geographically across England.

(Farmer 15).

Some farmers claimed that there was a lack of research on the topic, while others said that there was probably a great amount of research conducted, but that it was normally unavailable to farmers. The SNA showed that the majority of the farmers had no direct connection to the research community, however the picture is more blurred, as five individuals listed a total of ten researchers or research organisations as someone they would discuss their farming practices with, but only half of these were seen as highly influential.

5. Discussion

In accordance with a number of other studies on farmer networks (E.g. Wood et al., 2014; Isaac, 2012; Wick et al., 2018; Sligo, 2005; Sligo and Massey, 2007) our results show the importance of interpersonal sources of information and that farmers mostly talked with other farmers about their farming practices as they consider their successful peers to be reliable experts because of their practical experience under comparable conditions (Šūmane et al., 2018).

The ego-networks in this study were dominated by farmers with shared practice that expanded rapidly after implementing NT, a pattern aligning with the homophily principle in which contacts occur more frequently between individuals in homogenous groups than actors with more loosely tied and heterogeneous networks (McPherson et al., 2001). The SNA showed that the NT farmers had rather homogenous networks as the majority of the individuals were other farmers with shared practice. A strong connection between identity and farmers who see themselves as conservationists was also found by Sulemana and James (2014) when assessing the link between identity, ethical attitudes and environmental practices in a survey of 3000 Missouri farmers. The NT farmers in our study identified with each other as they viewed themselves as a separate community of farmers that were characterized by a fellow interest in NT practice. This concurs with other studies, such as Mann (2018), who assessed triggers for adoption of innovative conservation technologies in Switzerland and found that an important characteristic of NT farmers was that they shared a motivation to devote more attention to environmental issues than the other farmers in the study. Indeed farmers' participation in networks and a shared identity can increase their commitment to the ideologies and practices (Gray and Gibson, 2013). This homophily, expressed as sharing of a common goal, practice and identity, aligns to the conceptualisation of the networks as a Communities of Practice (CoP) which can both advance and constrain innovation (Morgan, 2011; Ingram et al., 2014).

The NT farmers in our study also preferred to communicate with each other as they believed that the level of knowledge amongst other NT farmers was high. The network was driven by each individual's ability and eagerness to communicate with and learn from other farmers and to find and acquire what they considered to be valid and trusted information. A study of young innovative farmers in Italy by Milone and Ventura (2019) found that the farmers' passion for their work and their land was a common theme amongst them. This led them to manage their farms in new ways, which was an important driver for the introduction of new farming practices that would reduce soil threats and give incentive to reach out to new markets and create partnerships with actors with similar values. NT farmers' ability to network with other NT farmers and find relevant information was seen as essential, confirming that farmer information networks are sustained by the need for a specific type of knowledge and fear of not succeeding when implementing challenging or novel farming practices (Šūmane et al., 2018). Tacit knowledge, embedded in practice, commitment and involvement in a specific context with a more personal quality, thus plays a central role in NT implementation and networking.

Intermediaries have an important role in the NT farmer networks in connecting farmers to each other and to other sources of information, or to the soil research community as knowledge brokers. Intermediaries connect different networks or clusters with far reaching information and knowledge network connections (Meyer, 2010). Farmers with core positions within their networks can act as intermediaries in disseminating innovative farming practices (Šūmane et al., 2018; Pei et al., 2014; Klerkx et al., 2012) while knowledge brokers play an important role in 'translating' science into accessible information for farmers, or transforming explicit knowledge from actors outside the group to tacit knowledge within the group (Bourne et al., 2017). Intermediaries also provide a link and information flow between the different clusters of farmers in the network. Information flow within networks often depends on a few outstanding individuals (Bourne et al., 2017), and such intermediaries or brokers mentioned by several farmers in our study appeared central and important both in connecting the network and building up a body of knowledge within it. These key individuals in the social network hold the majority of ties and the connections between these individuals draws the other actors together, as noted in other research (Wood et al., 2014). This is supported by the SNA measures of network cohesiveness which show that the farmers in the study are mostly connected by fellow contacts, and not by direct links to each other. The intermediaries in this study also had the role as influencers in inspiring farmers to convert and to provide information to farmers who were new to the practice. For NT farmers, other NT farmers with longer experience and similar goals to them who were passionate about what they were doing were often their main influencers, along with farmers who could demonstrate an increase in income despite spending less on inputs. The findings fit with the widely used concepts of early and late adopters, where the experienced NT farmers were the 'innovators' and the more recent adopters were the 'imitators' (Wozniak, 1993).

Previous empirical work on agricultural advice networks suggests that the most common source of advice is often regional actors, including agricultural advisers, and regional to national non-governmental organisations, followed by family and neighbours and other non-local businesses (Baird et al., 2016). In these cases, farmers with larger and more diverse ego-networks were more likely to implement Best Management practices. However, given the relative infancy of NT adoption, the lack of existing advisory networks and the particular knowledge needs required for implementation, NT networks tend to be more homogeneous and horizontal, with most connections within the (NT) farming community. NT farmers also perceived themselves to have higher levels of knowledge about NT than other actors such as researchers or external organisations, because of their practical experience. Our findings show that the level of knowledge and experience amongst NT farmers in this study was largely affected by farmers experimenting on their own farm and exploring new ideas and techniques, and communicating this experiential knowledge through informal learning networks, thus supporting previous work (Tran et al., 2019). Poncet et al. (2010) suggested from work in Morocco that farmers must be seen as the new local experts and that agricultural extension should focus on creating and sustaining innovation networks to facilitate knowledge exchange and interaction between individuals. In accordance with our study, they discovered that farmers use a wider range of knowledge sources and intermediaries, and that information diffusion of innovation between farmers was particularly important. Innovation was dependent on farmers' ability to interact and exchange knowledge and information, suggesting that extensionists should focus more on connecting different actors by network building, knowledge production and circulating (also to small-scale farmers), and learning from farmers how they practice, learn, exchange and innovate through their networks.

Studies show that knowledge pools are not equally accessible to all farmers (Ramirez, 2013), but we suggest that these differences were less pronounced within the NT farmer community where many of the connections were unlikely to be local, and the network often geographically distributed and virtual. Indeed, in our study, some of the greatest inspiration sources were farmers with long experience situated outside of England, particularly from America, where NT was more widespread. One likely explanation for this is that the formal advisory systems are not able to support the increasing requirements for diversified and complex knowledge by farmers (Poncet et al., 2010; Milone and Ventura, 2019), as noted for soil management in particular (Ingram, 2010; Ingram and Mills, 2019). The weak social ties to overseas farmers were therefore an important way for the English NT farmer networks to increase the internal information flow and benefit from the experiential knowledge pools of farmers with decades of experience. Granovetter (1983) reviewed the strength and role of weak ties in affecting cohesion in complex social systems. He concluded that one of the advantages of weak social ties is the effect on the diffusion of ideas and innovations, suggesting that individuals with few weak ties will be deprived of information and restricted to the ideas of their immediate network. Granovetter's findings underpin the importance of the geographically distributed networks of NT farmers in developing their practice with some individuals able to bridge externally to other networks to access new sources of information about innovative NT practices, while the strong social ties caused by homophily within the clusters have higher influence in terms of consolidating individuals' decisions and practices providing locally relevant knowledge.

It is notable in our study that farmers are linked remotely in distributed Networks of Practice (NoPs). Members of a NOP may never meet each other yet, like CoP, they share a common culture, know-how, practice and activities and are capable of sharing knowledge and identity (Brown and Duguid, 2001). Connections to these more geographically distant networks are made possible by information and communication technology (i.e. internet, smart phones and other communication mediums) (ICT) as shown in other studies (Šūmane et al., 2018; Mills et al., 2019; Eastwood et al., 2012). ICT have facilitated the development of a networking culture amongst young farmers in particular (Milone and Ventura, 2019) and specifically for soil, Mills et al. (2019) noted how social media can enhance sharing of experiential learning about soil and tillage management. Initially, learning within NT social networks with social media was quite superficial as farmers connected with each other to learn the essentials of how to 'do NT' but as they became more experienced, they shared more detailed knowledge about the soil health dimensions and the other benefits of NT.

NT farmers had the perception that they received very little support and understanding from the local conventional farmers. They described the level of knowledge about NT amongst farmers in their areas as poor, which was also pointed out as the greatest barrier to NT adoption. This aligns with a study by Samiee and Rezaei-Moghaddam (2017), which assessed predictive models for adoption of NT in Iran, indicating that the level of knowledge about the practice was one of the most important differences between adopters and non-adopters. Our findings also concur with Oreszczyn et al. (2010) who found that the introduction of agricultural innovations has the potential to strengthen or weaken farmers' Networks of Practice (NoP) by dividing or enhancing farming communities. In the case of NT farmers, the lack of knowledge of neighbouring conventional farmers about NT farming means that new adopters must look further afield for information and, therefore, their network becomes more dispersed and distributed. In other words they become more socially aligned to individuals in their NT network, who may be geographically distant, than their local farming neighbours (Liu et al., 2018).

Schneider et al. (2010) argued that Swiss farmers based their decision to adopt or reject soil conservation measures on common explicit and tacit understandings, including values and social norms ("life world"). Similarly, in our study NT farmers' image of themselves, their social norms seemed to strengthen their NoP, and by implementing NT farmers did not only adapt to a new practice by changing farm routines, but also changed their identity by adjusting their underlying values, the image of themselves and their perception of the aesthetics of cultivated fields. The importance of social norms was also shown by Isaac et al. (2007) who found that marginal individuals, like settler farmers, were more likely to take on core roles and introduce or adopt innovations due to less pressure for social conformity from peers.

6. Conclusion

NT has the potential to provide a number of beneficial agricultural and environmental functions, however its uptake in northern Europe is still relatively low. Like other systems that demand complex changes in practice, NT is characterized both by the need to develop situated and experiential knowledge, and to share this knowledge in the absence of support from the advisory services. SNA systematic methods used in this study show that social networks play a crucial role in the circulation of experiential knowledge about NT in this context in England. This analysis of the characteristics, dynamics and relations of these social networks, is a useful way of revealing the role of farmers and other actors in generating innovation in tillage systems. It complements previous research, which is largely qualitative, about farmer tillage networks with quantitative evidence. Notably it allows us to identify two leverage points in agricultural advisory systems where interventions could help to enhance uptake of NT and similar practices.

Firstly it confirms the importance of farm to farmer networks and provides support to the argument for agricultural advisory services to foster farmer innovation networks. Facilitation of knowledge by advisors requires understanding of how knowledge is produced and circulated within farmer networks (Poncet et al., 2010). Previously calls have been made to support groups through the CAP mechanisms (Brunori et al., 2013), and policy instruments such as Operational Groups (part of the EU Rural Development Programme) now offer such means. However, given the emergence and use of social media in the farming community in facilitating such networking, support or curation of such media should arguably become part of the advisory services portfolio. This questions the role of advisers in such support. Whilst their ability to provide the tacit knowledge, embedded in practice that farmers require for NT is limited, they can adapt their practices, skills, and capabilities to facilitate and support networking (Rijswijk et al., 2018; Poncet et al., 2010). Wick et al. (2018) describes how modern approaches can build upon traditional advisory approaches, by embracing social and knowledge networks concerning soil health. In this respect, advisory services can act as a boundary organization or knowledge network manager. Advisers can play a role in providing validity and scientific evidence and so assist farmers with critical assessment and interpretation of information (Wick et al., 2018). Advisers can also access institutional resources to provide the digital infrastructure and capacity to act as a moderator, which is often absent when it is farmer-led; and provide a single portal to access fragmented or dispersed networks.

Secondly the research highlights the key role of intermediaries and knowledge brokers. Identifying and enabling these intermediaries to be active in their connecting role could help to accelerate NT uptake. Their ability to connect different groups could also be harnessed to expand more insular networks or individuals, both with NT and other beneficial practices. Their bridging role in connecting non NT farmers and advisers to the large repository of knowledge that resides within the NT community is crucial. Equally the role of influencers is also revealed as important, particularly where the practice requires inspirational voices and its advancement is tied up with a common culture or passion. In social media contexts such 'opinion leaders' have been termed 'superspreaders' (Pei et al., 2014) and the potential of targeting them with important information for dissemination has been recognised.

The networks described here have been shown to support systems of actors that are achieving individual and collective goals (Engel, 1995) with the function of guiding, convincing, binding and mitigating uncertainties (Berkhout, 2006; Klerkx et al., 2010). However, their role in the wider AIS is not so clear. Studies looking at the interface between such networks and the AIS have revealed how innovation networks emerge in the absence of conventional AIS support, but equally that they can contribute to the overall performance of AIS and should be fostered by reforming the AIS to become more adaptive and flexible (Klerkx et al., 2012; Ingram, 2015).

This suggests that as well as supporting farmer NT networks with facilitation and network management, the AIS itself needs to provide space and legitimacy for such networks. The SNA approach is a useful tool for mapping farmers' social networks. It was, however, limited to mapping current networks of the participants and the snowball approach to recruitment may over-emphasise the connections within the network. Further, people who the farmers followed online but did not directly interact with were not included in the SNA, perhaps distorting the broader picture of farmers' influencers. The identification and recruitment of some of the farmers through Twitter can also overemphasize the role of social media platforms in facilitating communication between NT farmers. More evidence is needed to fully understand the dynamics and characteristics of NT farmer networks and future studies would benefit from repeating the SNA mapping, for example both before and after implementation of NT, to provide a more thorough analysis of the temporal changes in farmers' networks with NT adoption. Further assessments of the global farmer networks are also needed to understand the diffusion of knowledge and uptake of technology resulting from links between farmers across countries.

Author contributions

The authors have no competing interests to declare. All authors conceived the idea and contributed to the planning. KS undertook the literature searching and analysis and lead on the writing. All authors contributed critically to the drafts and gave final approval for publication.

Declaration of Competing Interests

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

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Appendix A. Supplementary data

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8 Paper IV

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SPECIAL ISSUE PAPER

WILEY Soil Use and Management

The use of Twitter for knowledge exchange on sustainable soil management

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Abstract

Encouraging the uptake of sustainable soil management practices often requires on-farm experiential learning and adaptation over a sustained period, rather than the traditional knowledge transfer processes of identifying a problem and implementing a solution. Farmer-to-farmer learning networks are emerging with farmers experimenting and sharing knowledge about these practices amongst themselves. One potential communication channel for such interaction and knowledge sharing is social media and Twitter in particular. A content analysis of a Twitter account for an EU research project, SoilCare, and in-depth qualitative interviews with five farmers using Twitter, was used to illustrate the extent and type of farmer-to-farmer knowledge sharing in relation to sustainable soil management practices. Evidence of farmer learning and knowledge sharing on Twitter with respect to these practices was identified. Twitter can capture the immediacy of the field operations and visual impacts in the field. Furthermore, the brief messages channelled through Twitter appeal to time-constrained farmers. The ability for interaction around particular hashtags in Twitter is developing virtual networks of practice in relation to sustainable soil management. Within these networks, farmer champions are emerging that are respected by other farmers. Twitter works best for those actively seeking information, rather than passive recipients of new knowledge. Therefore, its use with other forms of face-to-face interaction as part of a blended learning approach is recommended. Twitter also offers a potential space for other actors, such as researchers and advisers, to interact and share knowledge with farmers.

KEYWORDS

farmer learning, knowledge exchange, social media, sustainable soil management, Twitter

1 | INTRODUCTION

It is widely recognized that some farming practices within European crop production are reducing soil quality which in turn is affecting productivity (Jones et al., 2012). Currently, production levels are maintained by increased use of agricultural inputs and technology that may reduce profitability due to their costs, whilst also negatively affecting the environment (Rockström et al., 2009). Sustainable soil management (SSM) practices are required that both improve the quality of the soil and increase productivity. In a European context, such practices might include crop rotations, cover crops residue management, reduced tillage operations, fertilizer and manure management to restore soil carbon. It is the aim of SoilCare (Soil Care for profitable and sustainable crop production in Europe) (www.soilcare-project.eu), an interdisciplinary research project funded by EU Horizon 2020, to identify and test soil management practices appropriate to particular pedo-climatic and socio-economic conditions that have the potential to optimize soil quality and crop productivity across Europe.

Whilst the potential of these SSM practices to improve soil quality and productivity is recognized amongst the scientific community, their uptake by farmers across Europe has been slow (Lahmar, 2010). There are certain characteristics of SSM practices that we consider below that mean their uptake might not follow traditional innovation adoption processes. Instead, there is an interesting emergence of farmer-to-farmer learning networks with farmers experimenting and sharing knowledge about these practices amongst themselves.

One potential communication media for sharing knowledge and interactive communication process is social media and in particular Twitter (twitter.com), one of the most widely used social media tools. Evidence is emerging of the use of Twitter accounts for communication and learning in other sectors, such as engineering (Palmer, 2016) and the medical and healthcare sectors (Grajales, Sheps, Ho, Novak-Lauscher, & Eysenbach, 2014), but to date, there is limited information on the use of Twitter for learning and knowledge sharing within the agricultural community.

The aim of this paper, therefore, was to use the SoilCare Twitter account, which currently has over 1,200 followers, to explore the extent and type of farmer-to-farmer knowledge sharing in relation to SSM practices. This outcome will be achieved by profiling those who are following the SoilCare Twitter account, analysing tweets related to particular SSM hashtags and interviewing a select number of farmers following the SoilCare Twitter account to illustrate their social media usage.

2 | LITERATURE REVIEW

2.1 | Social media and farmer-to-farmer learning

Traditionally, within agricultural extension models, the dissemination of new knowledge was conceptualized as a linear process from a central point to the land manager (Röling, 1992). These traditional extension models assume that innovations (and knowledge) originate in science and are transferred to land managers who adopt them. This "knowledge transfer" approach to advice focuses on knowledge production, communicative intervention and knowledge consumption (measured as behavioural change). More recently, bottom-up "human development" approaches have emerged which are based on the principles of participation, empowerment and ownership of the problem (Röling & Jiggins, 1994). The implication is that, given the right conditions, information, mutual interaction and opportunity, land managers will develop their own appropriate solutions to their problems. The process is one of experiential learning, rather than passive knowledge utilization.

Extension or advice based on the linear model is seen as appropriate for the promotion of discrete technologies or seasonal operations, such as sub-soiling. Sustainable soil management, however, is not only concerned with individual technologies but also establishing different ways of thinking about the management of complex and locally variable systems, sometimes requiring systemic changes. Moreover, the benefits of SSM practices are not immediately apparent and are often only realized in the medium to long term. It can take several years for improved soil quality to impact on crop yields, and the improvements in soil are not always immediately observable. As a result, help with on-farm experimentation and adaptation is required over a sustained period, rather than the traditional knowledge transfer processes of identifying a problem and implementing a solution (Darnhofer, Bellon, Dedieu, & Milestad, 2010). A more adaptive approach is required, one of "act, monitor, learn, adapt" (Burton et al., 2007). This process of experiential learning can be enhanced through social interaction and knowledge sharing with others in the same situations (see Fry and Thieme, this issue).

One potential opportunity to facilitate increased social interaction and learning within the agricultural industry is the use of social media, which globally is increasing rapidly. There were 2.46 billion social media users around the globe in 2017 and this is expected to rise to 3.02 billion by 2021 (Statista, 2018). However, current emphasis is placed on instrumental uses of social media for disseminating information and transferring messages, compared to a more dialogical form of communication which engages users in reflective and problem-solving discussion (Chowdhury & Odame, 2013).

From the literature, it would appear that social media can have a number of functions within the agricultural industry, namely marketing and consumer engagement; lobbying and campaigning; networking and knowledge sharing; and crisis communication (see Table 1).

Increases in the use of social media amongst the agricultural community have been particularly noted in the literature in United States, Canada, Australia and UK (Chowdhury & Odame, 2013; Stanley, 2013). Although to date, social media have largely been used successfully in the agricultural industry for marketing and lobbying, there is greater potential for its use as an interactive, learning and knowledge sharing global platform (Stanley, 2013) (see Wick et al., this issue).

Some notable examples of knowledge sharing platforms are starting to emerge, for example the #Agchat discussion forums, which are weekly moderated Twitter discussions that were initially founded in the United States and now operate in UK (#Agrichat), Australia (#AgChatOZ) and New Zealand (#AgChatNZ). Also, various farmer communities of practice are starting to develop, such as #clubhectare in UK, which started with a group of farmers discussing arable

TABLE 1 Social media functions in the agricultural industry

Social media functions	Examples of usage	References
Marketing and consumer engagement	• Increase product/brand awareness • Enabling farms to connect with customers • Building trust with customers • Increasing traceability	Chowdhury and Odame (2013); Stanley (2013); Bos and Owen (2016); Morris and James (2017); Kaushik et al. (2018)
Lobbying and campaigning	• Bringing together a collective voice to campaign for change • UK #sosdairy campaign in which Twitter was used to raise awareness of the problems of the dairy industry	Stanley (2013)
Networking and knowledge sharing (farmer-to-farmer)	• Interaction with other farmers, nationally and globally. • Joint learning and knowledge co-creation • #AgChat discussion forums	Stanley (2013); Materia, Giarè, and Klerkx (2015); Phillips et al. (2018)
Crisis communication	• A channel for communicating problems or issues within the agricultural industry.	Stanley (2013)

farming-related issues on Twitter, who then decided to meet up socially. The group now has 342 members and is growing globally (Stanley, 2013).

Whilst there is evidence of increased use of social media amongst the farming community, there appears to be a reluctance to use it as an outreach platform amongst farm advisers (Newbury, Humphreys, & Fuess, 2014; Suchiradipta & Saravanan, 2016). Reasons for this relate to concerns about lack of skills and competency and perceptions about the time required to engage in social media (see Jenkins et al., this issue) and loss of control over messages posted, related to a sense of responsibility for the messages (Newbury et al., 2014; Suchiradipta & Saravanan, 2016).

2.2 | Twitter usage in agricultural industry

Different social media platforms (e.g. blogs, Facebook, LinkedIn, Twitter and YouTube) have different functions. This paper focuses on one particular form of social media, Twitter, which has been promoted as a tool for collective learning processes and the co-creation of knowledge (Chowdhury & Odame, 2013). Twitter is a microblogging platform in which users can currently publish messages of up to 140 characters, and towards the end of 2017, it had 330 million monthly active users globally. The use of Twitter has proliferated with the increase in smartphones. An online survey of UK and French farmers in 2014 found that 89% of respondents owned a smartphone, 84% used it for farm management and 72% used it on a daily basis (Dehnen-Schmutz, Foster, Owen, & Persello, 2016).

Individual users of Twitter adopt a "handle" which is distinguished by an @ sign. Users can mention other users by using their handle or take part in wider debates by using an indexing term denoted by the use of a hashtag or #. It is also possible to follow the tweets of particular users. This allows people to organize their interests or activity in Twitter by communities of interest or social networks. The system also allows users to connect to other forms of Internet-based media, and this is a very common use of Twitter to link to longer or more detailed information. Users can post links to web pages, photographs, videos or audio files, as well as use the Twitter space for their own compositions. With the exception of tweets from protected accounts, all tweets are publically available. Retweeting and replying to the tweeted posts indicate expressions of intentional communication. A higher level of retweeting is seen as an indicator of a more active engagement and interaction in the Twitter environment, rather than simple one-way communication (Simply Measured, 2014).

It is this more active engagement and interactive use of Twitter that is the focus of this paper. We wish to explore whether there is potential for Twitter to drive the uptake of SSM by engaging others as well as facilitating discussion amongst various actors (e.g. farmers, researchers, knowledge brokers, policymakers and entrepreneurs). Does Twitter have the potential for creating a learning environment where there is a knowledge sharing from experiences of implementing SSM practices?

3 | METHOD

This paper was based on twin streams of data. Firstly, data were derived from an online analysis of the SoilCare Twitter account. The account was first established in 2016 to support the dissemination activity of the SoilCare project, with almost daily activity targeted at all users interested in soil research. The account gained 1226 followers over 21 months between

11 March 2016 and the 22 December 2017. Secondly, to provide illustrative examples of Twitter usage, qualitative interviews were conducted with five farmers who are active Twitter users.

Using Twitonomy and the Ncapture facility of the qualitative analytic software, Nvivo 11, we collected the entire Twitter feed of @SoilCare_eu which allowed us to consider not only who follows the account but their interactions and some of the content of their responses. We initially undertook a profiling of each user to ascertain the interests of those following the SoilCare Twitter account. Using Twitonomy, we were able to collect the Twitter profile descriptions of each of the 1226 followers and then manually place them into one of 8 predetermined user categories based on their profile description. We then focused on analysing the Twitter activity of those describing themselves as farmers. Amongst these farmers, the number of tweets ranged from 10,397 to 5, suggesting some very active farmers and some less so. We were able to collect data about these farmers' Twitter accounts and in this way were able to follow the networks of interaction and influence around particular hashtags and accounts, looking for incidences of sustained discussion, from the starting point of @SoilCare_eu.

To understand more fully farmers' use of Twitter for supporting SSM, we undertook in-depth, qualitative interviews with five farmers who are active in using Twitter to discuss SSM. A semi-structured questionnaire was designed with 24 questions derived from an analysis of the key issues in the literature and structured around two key themes: the reasons for using Twitter and details about the practical use of Twitter. A farmer following the SoilCare Twitter account, who actively discussed SSM issues, was contacted initially via the Direct Message facility on Twitter and a telephone interview arranged. A chain referral sample (snowballing) approach was used to identify further interviewees, by asking farmers for others with whom they interacted about SSM on Twitter. This approach proved an effective way of gaining access to a population in an efficient way. The interviews lasted between 30 min and 1 hr. The interviews were transcribed and a content analysis undertaken to identify key statements that illustrated the farmers' use of Twitter. The data were first coded into broad categories using a priori deductive codes, such as "reasons for use of Twitter" and "practical use of Twitter." The second stage of the analysis took an inductive approach to further coding, capturing common themes. All the farmers were from the UK and covered a range of ages, farm type and farm size (Table 2).

These interviews aimed to illustrate Twitter usage for sustainable soil management by farmers actively using Twitter. As only five interviews were conducted, their use is limited to indicative purposes only. Further interviews are recommended for future research that fully explains the underlying processes in farmers' Twitter usage.

TABLE 2 Details of farmers interviewed

Farmer	Age	Farm type	Farm size
AH	38	Arable	330
AB	47	Mixed	450
D	35	Arable	900
M	48	Arable	800
W	51	Mixed	1,250

TABLE 3 User categorization and frequencies of followers of @SoilCare_eu

Category	No.	% of total
Scientist/researcher	286	24
PhD student	69	6
Science project/programme	52	4
Commercial business/product/ service	181	15
Farmer adviser/agronomist/ trainer	89	7
NGO/campaigner/forum/ commentator/media	126	10
Farmer/grower/farm manager/ contractor	123	10
Policymaker	9	1
Uncategorized	271	22
Total	1,206	99

As Twitter is in the public domain, some have argued that academic analysis is unproblematic. However, as authors, we contend that few who post on Twitter realize the insights that can be gained from sustained scrutiny and that obtaining informed consent from all participants is impractical (Reed & Keech, 2017). Therefore, in reporting the results, we have anonymised the comments of participants.

4 | RESULTS

Our initial analysis of the 1206 followers of @SoilCare_eu showed that the majority of followers were from the scientific community (24%), and 6% were PhD students (see Table 3). This result is unsurprising given that SoilCare is a scientific research project. Interestingly, 10% of the followers identified themselves as farmers, growers or farm managers. In comparison, there were fewer followers from the farm advisory services (7%) and there were a particularly small number of followers from the policy community (1%).

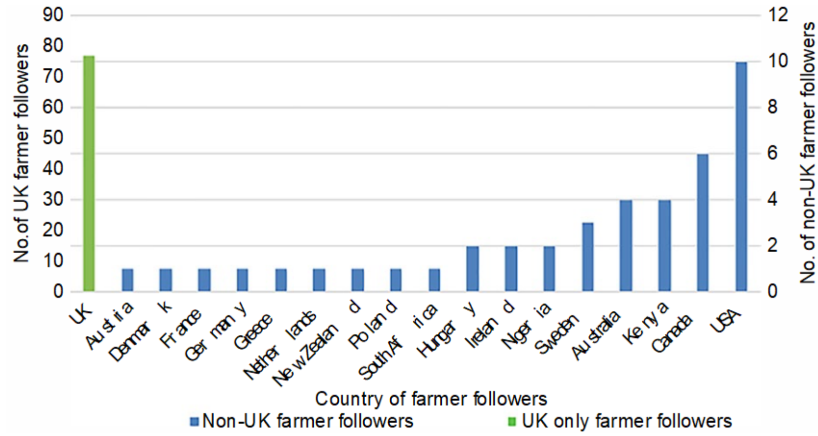

FIGURE 1 Number of @SoilCare_eu farmer followers by UK and non-UK countries. [Colour figure can be viewed at wileyonlinelibrary.com]

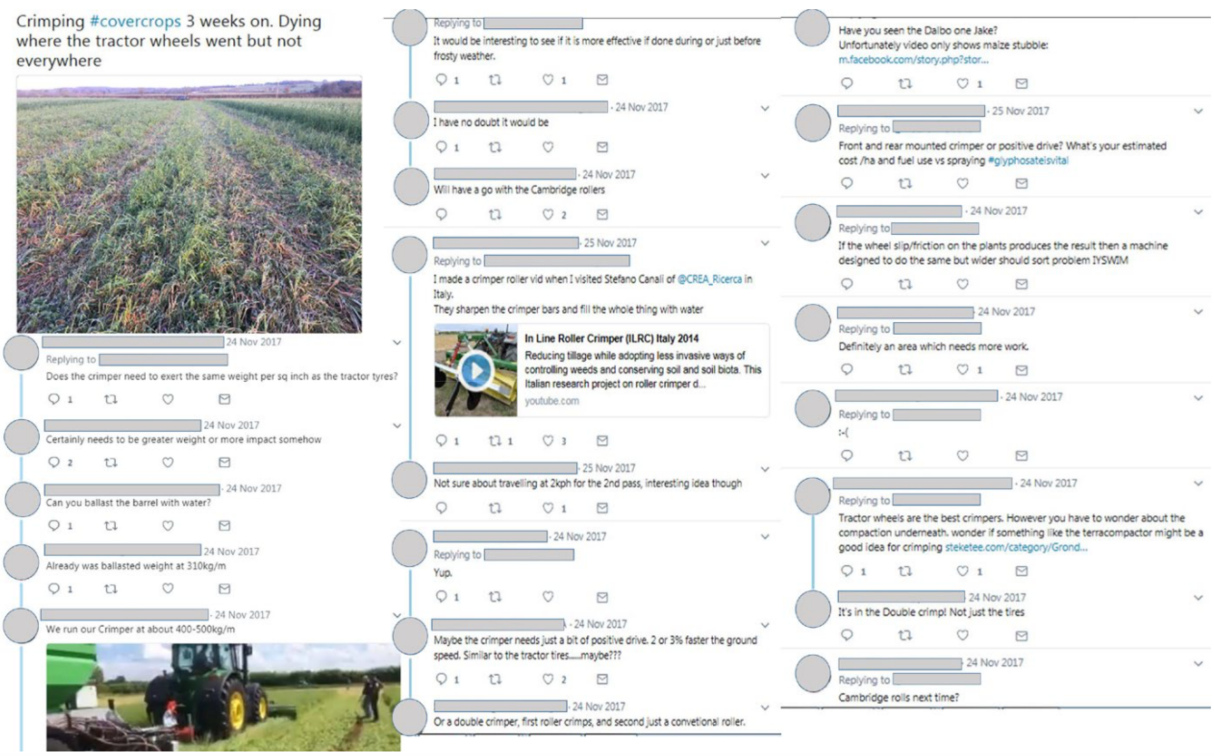

FIGURE 2 Extract from a Twitter discussion on terminating cover crops. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 1 shows the majority of the followers in the farmers/growers/farm managers category came from the United Kingdom (64%), with others from United States, Canada, Australia, other European countries and Africa.

If we consider the numbers of friends, followers and tweets posted, the farmers stood out as being particularly active on average, posting over a third as many Tweets as other categories. The mean number of tweets by farmers was 3,972, the average number of followers was 1,451 and the average number of people they were following was 1,216 (total sample average: tweets-2,547; followers-538; and followed-1,073). Therefore, farmers were more active in posting onto Twitter, were more likely to be followed, but only a little more likely to be following others, which made them active and potential influencers. Whilst the paper is focused on the farmer participants in the Twitter feed, it is clear that this was a heterogeneous group, using Twitter for different reasons and pursuing different strategies (Table 3).

Within this group of farmers was a subset who were both particularly active, but also influential. Farmer SF was the most active and had posted over 100,000 tweets. He was followed by over 13,000 people and in turn followed over 10,000 (a followers:following (FF) ratio of 1.26). This suggests an approach to Twitter of high volume postings and reciprocal following. Farmer Alpha had a distinctive profile. He had posted over 24,000 tweets, had 9,500 followers, but he was only following 1,795 people, a FF ratio of 5.26, which indicated that other people were listening to him. The tweets of farmers such as Farmer Alpha and Farmer SF included several hashtags, suggesting that they were coordinating their discussions through indexing terms that they know and control.

In the period November 2017 to February 2018, we collected tweets from the @SoilCare_eu Twitter feed using indexing terms for two SSM practices, 300 were using #covercrops and 394 using #notill. A single tweet can contain several indexing terms so in this way people can participate in several concurrent discussions, also this can cross languages with, for example, Spanish language tweets including an English indexing term. This means that these threads of conversation can cross languages, nations, time zones and bio-physical conditions, gaining participants who contribute a range of media and perspectives.

Figure 2 illustrates a simplified extract of part of a conversation initiated by Farmer Alpha using the #covercrops hashtag and a photograph of a field that he had "crimped"[1] which had been only partially successful. A discussion emerged over 2 days about the practice, which led to a sharing of practical knowledge and consideration of alternative approaches. In the end, the exchange drew in 18 farmers and one CEO of an NGO, of which 15 were based in UK, but three from other countries (United States, Canada and Germany). This seemingly quotidian discussion included photographs, emoticons, videos of machinery in operation and technical details as well as jokes and references to the wider context of the farming sector. Even in this simplified form, the social, technological and symbolic sophistication of the exchanges is evident. Also, it was a highly efficient way of gathering information; within a short exchange, questions about the operation and supply of the equipment were dealt with and included an opportunity to see one machine in operation, as well as finding a source of such equipment. As a published discussion, it remains visible and available to others searching through the index terms #covercrops.

Whilst this extract provides a useful example of how Twitter can be used for farmer-to-farmer learning, the interviews provided more details to illustrate how Twitter is being used by farmers for knowledge sharing and learning.

[1]Crimping—use of bladed roller designed to roll, cut and bruise cover crops before drilling.

4.1 | Reasons for use of Twitter

All the interviewed farmers were self-taught in the use of Twitter. Two interviewees said that they opened an account after becoming a Nuffield Scholar[2], as Twitter was promoted there. An important influence on the use of Twitter was the need to seek information about innovative farming practices, such as Conservation Agriculture, when "looking over the neighbour's fence" for advice was no longer sufficient. Twitter provided the opportunity to interact with farmers all over the UK, as well as Europe and the wider world.

> "...you don't just go to your neighbour farmer, because it is not happening there, but on Twitter you can get hold of people from all around the country, and indeed Europe and America, and Australia with the same practices" (Farmer AB).

The speed of response and convenience of Twitter was also an important factor in its usage:

> "...I guess it is convenient for me as I have always got my phone on me, and there are odd times when I am being in a tractor or in a vehicle stopped or just walking somewhere and you can really quickly access it" (Farmer W).

Farmer M said he thought Twitter was well suited for farmers as they are not in any direct competition and more likely to collaborate with each other as "*...there is no commercial edge to be had.*"

The impacts on the business were in the realms of providing inspiration and an extra stream of information as well as making the job more interesting. Interaction on Twitter could broaden the farmer's outlook and generate more questions about their practices:

> "...it has given me, as a manager, more of a wider interest in different things instead of just carrying on with what I have always done or what is done locally, from looking over the hedge, now you are looking on a national scale" (Farmer M).

The use of Twitter for networking was important to the farmers, either actively or by happenstance "*...I don't actively use it for networking, it just happens" (Farmer M).* The network was mainly other farmers, and often those with the same farming practices, although Farmer AH said that he followed farmers doing different things from himself to prevent being in a

[2]A UK scholarship that funds up to 20 individuals a year to research topics of interest in either farming, food, horticulture or rural industries. Scholars can travel anywhere in the world to further their knowledge and understanding of their chosen study topic.

"bubble." Researchers working with related subjects often were part of the network, and agronomic information was welcomed as an important contribution to the farmers' knowledge. They all had a common view that their Twitter networks were purely business related, whilst other social interaction would be more likely to happen on *Facebook* or *WhatsApp*. They explained that they would follow someone if they found them interesting at the time and unfollow them as soon as they lost the interest.

Twitter was also seen as a good starting point for getting more information or to discuss new ideas. It is a useful platform to figure out other farmers' past experiences with a certain type of practice: *"…you get bullet points through Twitter - it is a gateway" (Farmer M)*. The farmers said they were interacting and sharing knowledge on Twitter, as well as asking questions. They were mainly influenced by groups of farmers or individuals that they respected, while they were of the impression that they mainly influenced those farmers doing similar things as themselves. However, Farmer AH, Farmer AB, Farmer D and Farmer M acknowledged their potential role as brokers of information (although farmer M said that he does not try to be a disseminator, but that he is sharing and wants opinions back). Farmer AH and Farmer M were taking this role on to get reactions and opinions back from all around the world, whilst Farmer AB and Farmer D seemed to be more driven by the idea of contributing to sharing knowledge, as people had shared with them in the past.

> "…as people have shared information with me in the past, I feel like I should return the favour" (Farmer D).

4.2 | Practical use of Twitter

The farmers did not use many hashtags, those mentioned were: #notill, #rootsnotiron, #harvest17, #crosslot, #soilhealth, #ironnotroots, #ilovefarming and #Farmersfit. Pictures were largely used and seen as an important form of communication:

> "…obviously it is very easy for me to say that I have got a lovely oilseed rape bean companion crop or whatever, but if I actually put a picture of it up there it has much more impact…" (Farmer AB).

Most of the farmers seemed to have good experiences with asking questions on Twitter and thought their network had much of knowledge that could benefit them. Four of the farmers used Twitter actively for learning, whereas one farmer said that he only used it to get in contact with people, but may utilize their network for learning in the future. Although Twitter was seen as a good tool for learning, non-virtual interaction was still valued as the better way, especially if you are standing in the field talking about the relevant practice. The farmers predicted more innovative farming as a result of Twitter usage. The reason for this is that it provides inspiration to try new methods from observing practices of others on Twitter.

The farmers had different expectations to the future of learning amongst farmers through the use of Twitter. As they did not think any other social media were better for the purpose of knowledge exchange or more user-friendly, they mostly expected that the Twitter usage would increase with new and younger farmers.

The extent of Twitter usage was described as a bit of an explosion during the last few years. Farmer AB related how at a meeting he attended a few years ago, where the participants were asked how they preferred to receive information, he was the only one in the room raising his hand when asked about Twitter. He expected that the situation would be quite different today.

5 | DISCUSSION

Clearly, our findings indicate that Twitter does have the potential for farmer learning and knowledge sharing with respect to SSM. In fact, Twitter appears to be particularly suited to SSM as it can capture the immediacy of the field operations and visual impacts in the field. Furthermore, the brief messages channelled through Twitter appeal to time-constrained farmers.

It would also appear that the ability for interaction around particular hashtags in Twitter has the potential to develop virtual networks of practice in relation to SSM. These are mainly networks of peers, which is significant in the context of studies of how farmers learn and whom they most trust (Sutherland et al., 2013). Within these networks, farmer champions can emerge that are respected by other farmers (see Wick et al., this issue). It was felt that observation of practices used by other farmers on Twitter who were respected and trusted as sources of information was likely to provide the inspiration for others to try new practices. Within our analysis, there was evidence of some highly interactive and influential farmers, with a larger number of followers. Currently, it appears that younger and more innovative farmers are interacting on Twitter, but as discussions are publicly available, the information is accessible to all. Also with respect to sharing learning, Twitter allows the process of individual experiential learning and adaptation to be enhanced through social interaction and knowledge sharing with others in the same situations (Darnhofer et al., 2010). Our findings suggest that Twitter can provide a dialogical form of communication, which engages users in practical problem-solving discussion, contrary to Chowdhury and Odame's (2013) findings that amongst Canadian agri-food and rural stakeholders, Twitter usage was for simple message exchange.

One distinct constraint of Twitter for the agriculture community relates to geographical inequalities resulting from poor technology infrastructure in some rural areas of Europe (Bos & Owen; Morris & James). However, with increasing density of smartphone availability and rural bandwidth, Twitter is a technology that will become increasingly accessible to most people without the need for specific training.

Despite these technological constraints, the interviewees reported that Twitter has many advantages; it is available to all and has lower social barriers to participation compared to other forms of social media, it also allows for much wider networking and access to a variety of resources, ranging from photographs through to peer-reviewed research. As reported in the interviews, other platforms such as *Facebook* and *WhatsApp* are used alongside Twitter, but for other purposes, both benefiting from and being disadvantaged by having higher social barriers (Thakur, Chander, & Sinha, 2017).

Certainly, we can see, even in this relatively small sample of data, indications of the development of virtual communities of practice. The combination of the smartphone, 4G mobile services and Twitter satisfies some of the preconditions for such communities, as identified by Hansen and colleagues, of collaborative tools that enable sharing and co-creation (Hansen et al., 2014). However, in the interviews, the importance of face-to-face interaction was also very clear. Meeting in the field is particularly important for soil which has sensory elements that farmers like to engage with via touch, smell etc. that can only be achieved on the ground. This points to the importance of "blended learning" approaches which combine the online with the offline knowledge exchanges (Cullen, Amos, & Padel, 2016).

The complex and sophisticated capabilities of Twitter discussions open opportunities to transcend social and geographical barriers. Our interviews and the number of farmers following @SoilCare_eu indicate that farmers are prepared to access the results of scientific research they find on Twitter. However, the interactions were largely farmer-to-farmer with little evidence in the farmer interviews or Figure 2 of scientists and advisers interacting directly with farmers through Twitter. This suggests that there is the potential for such actors to become more involved in engaging directly with farmers through social media platforms. The range of people following @SoilCare_eu would indicate that there is an opportunity for greater exchange amongst different actors through more active Twitter strategies, particularly if social media are used as an iterative, rather than a passive one-way process (Kaushik, Chowdhury, Hambly Odame, & van Paassen, 2018; Phillips, Klerkx, & McEntee, 2018). Significantly, although we searched in English, hashtag discussions appeared in other languages, indicating new opportunities for exchange and discussion across countries and continents.

6 | CONCLUSION

Our content analysis of the @SoilCare_eu Twitter account and the analysis of the farmer interviews have clearly identified an existing use of Twitter to share knowledge between farmers about practices related to SSM. We identified examples of knowledge sharing, using photographs, videos and links to scientific publications and reports. The immediacy and convenience of this platform are considered advantageous. Also, farmers are willing to share information in relation to SSM in this space as the topic is not considered commercially competitive. At the moment, Twitter usage by farmers appears concentrated in particular countries, but as the technology becomes increasingly more accessible, the Twitter community will grow with opportunities to share knowledge across countries and continents.

Twitter is seen as a useful source of additional information and particularly important for generating new ideas. However, farmer preference is still to share knowledge and learn from others in a face-to-face environment. Consequently, we conclude that there is potential for a more deliberate use of Twitter for combined virtual and non-virtual blended learning approaches in relation to SSM.

Finally, much of the knowledge sharing activity in relation to SSM on Twitter is taking place between farmers. There is an opportunity for scientists and advisers to engage with the discussions and conversations on SSM and use this space to interact and engage with farmers on the topic.

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9 Discussion

The aim of this interdisciplinary research was to contribute to knowledge about the effects of NT on soil functions, and to provide an in-depth understanding of the information networks of the NT farming community. The knowledge about the impact of NT on soil functions in NW Europe is limited, therefore a comparative study was undertaken in a commercial farming setting to provide improved understanding of the implementation of this farming system on different soil types and under the local weather conditions in a case study in the UK. Studies reflecting on the social dynamics of farmer networks in relation to NT implementation decisions are rarely conducted, therefore this study sought to understand farmer decision-making and the information flow and knowledge exchange crucial to successful implementation of new and innovative farming practices. The sections below summarise and discuss the main findings from the four paper chapters (Chapter 5 to 8) in light of the overall thesis objectives that were outlined in Chapter 1, and ends with a discussion of the limitations of the study.

9.1 The effect of NT practices on soil water functions

The first objective was to collate the current knowledge on the effects of NT practices on the soil functions of water purification and retention in NW Europe, and to assess alignment across the literature on the separate NT practices. To address this objective a comprehensive literature review (Chapter 5) of post-2000 studies of NT practices (direct drilling, cover crops, crop rotations and stubble management) was carried out.

The literature review identified that NT has varying effects on the water purification and retention functions of soil in NW Europe, often with conflicting findings, highlighting the complexity of the system. Fewer studies to-date have been conducted in NW Europe compared to other parts of the world where NT is more widespread, so this limited evidence might explain some of the variability in the findings. There was, however, consensus on some characteristics relevant to the water purification and retention soil functions. In particular, the beneficial effect of reduced erosion rates under NT practices, that is in turn reducing soil loss through runoff and particulate P to watercourses (Ulén and Kalisky, 2005, Schoumans et al., 2014), resulting from the higher aggregate stability and the protection of the soil surface by cover crops and crop residues, where these are used with NT. There is also consensus that NT practices lead to increasing DRP losses (Schoumans et al., 2014, Ulén et al., 2010, Ulén and Kalisky, 2005) as a result of the enhanced levels of plant material, and the stratification of SOM and nutrients in the topsoil under this practice (Fernández-Romero et al., 2016), with potentially greater implications for water quality (Taylor et al., 2016), as DRP is the bioavailable form of P that is quickly taken up by biota. The effect of NT on other soil properties, such as hydraulic conductivity, infiltration rate and water holding capacity, is more uncertain and should be explored further as there are indications that these variables are more dependent on local site conditions. Similarly, the effect of NT on the water retention function was highly dependent on soil texture, climatic conditions and other management factors such as crop rotations, type of cover crops and timing of field operations.

Cover crops are crucial for overall NT performance by reducing the potential negative effects of NT on soil structural properties and nutrient leaching (Bodner et al., 2013, Burr-Hersey et al., 2017, Abdollahi et al., 2014, Cooper et al., 2017). For example, there is consensus that NT does not reduce N leaching unless combined with a cover crop, as these crops are contributing to rapid uptake of excess N from the soil (Cooper et al., 2017, Constantin et al., 2010, Taylor et al., 2016). The uptake of P by crops and cover crops is slower than for N, so the cover crops were therefore less efficient in reducing P leaching (Taylor et al., 2016). Cover crops can also contribute to habitat improvement for soil biodiversity like earthworms, mitigating compaction damage of top soils and suppressing weeds, but the effect varies with species and crop type, and the root and canopy characteristics should be considered along with the specific challenges that farmers are facing connected to local conditions and soil type (e.g. soil compaction, erosion risk, nutrient leaching). More studies considering what combinations of cover crops are most beneficial to address site specific challenges on different soil types are therefore recommended.

Conducting detailed assessments of the soil and local conditions before introducing a new farming practice is particularly important in NW Europe, as the wetter and colder climatic conditions in this region can make the implementation of NT practices more challenging than in drier and warmer climates where NT is important for soil water conservation. There are still uncertainties regarding the potential role of NT to enhance soil functions related to achieving

WFD management objectives, as discussed in Chapter 5, and more research is needed to fully understand the effect of NT in NW Europe and to understand the trade-offs between soil functions under different local soil and weather conditions.

9.2 The applicability of NT in the UK

To contribute to fill the knowledge gap found in the literature review (Chapter 5) and summarised in the last section (9.1) regarding the impact of NT on soil functions in NW Europe, a monitoring programme was established to assess the effects of NT practices on the separate soil functions of water purification and retention; representing **the second thesis objective**. This comparative UK case study was carried out in a commercial farming setting to provide improved understanding of the implementation of NT and CT farming systems on different soil types and under the local weather conditions.

There are a number of variables that determine the applicability of NT that vary with local conditions. Soil structure is important to determine the impact of a new farming system, but can be difficult to monitor as this is a very slow response variable; with changes occurring over long timescales and the real effect only being visible after several years of carrying out the practice (Smith et al., 2013). Establishing field monitoring that lasts long enough to detect the long-term changes can be challenging. To go some way in overcoming this, **the third objective** of assessing the applicability of NT as a ‘sustainable’ practice in the UK by evaluating the shift from CT to NT and its potential to enhance soil functions, focusing on water purification and retention functions, was achieved by carrying out a 2-year monitoring programme on two commercial farms (Chapter 6).

The effect of the different farming systems was largely determined by soil type and the variance could be as high within, as between, the fields of NT and CT. Changes in soil structure were evident between the two practices with increased bulk densities under NT, indicating a higher degree of soil compaction within these fields. The temporal variability was, however, more significant under CT as the bulk density decreased due to tillage and increased with time to the same level as under NT in the autumn as a result of densification processes. One of the key soil structural indicators is SOM and this was found to be higher under NT, with a strong positive correlation to the soil moisture levels of the fields. The effect of NT on SOM was, however, highly dependent on soil type with substantial differences between practices in the free draining porous limestone soil, indicating that there were greater benefits to implementing NT on this type of course, free-draining soil of weaker structure than the finer lime-rich loamy soil. In the UK NT is primarily practised on self-draining calcareous soils as they self-mulch and produce good tilth from the wet-dry and freeze-thaw cycles (Davies and Finney, 2002), supporting these findings. The elevated moisture content retained in the soil under was particularly beneficial during the dry summer months when the CT fields in this study had higher water deficits. Higher SOM and soil moisture levels have implications for the chemical processes of soils and more denitrification is likely to occur under more anaerobic conditions caused by soil saturation, resulting in a decrease of the plant available NO_3 and an inverse relationship with SOM, as NO_3 is reduced to gaseous forms of N. There were higher concentrations of plant available PO_4^{3-}, also referred to as DRP, in the water samples that were collected downstream in NT fields than CT, which is in line with the findings from the literature review (Chapter 5) and a likely effect of leakage from the increased amounts of plant material cover on the surface of the NT fields compared to the CT fields.

This study underpins the importance of evaluating and comparing the effects of different farming systems on soils of different characteristics, texture and mineralogy. Applying a 'catch-all' indicator and/or recommendations across soil types and other local factors poses a risk regarding the success of the system, but the spatial variability related to land use and chemical, physical and biological processes is still poorly understood (Peukert et al., 2012).. The monitoring also demonstrated that assessing the inter-field and in-field variability by establishing a robust sampling strategy, both vertically and horizontally in the field, was important as the spatial and vertical distribution of nutrients vary temporally. Therefore, it is recommended to sample at several depths, and across multiple sites in a field, to properly understand the soil characteristics and avoid misrepresentation of results. The research community needs to be aware of the variability both within and between fields and the different outcomes of the same practice under different soil and weather conditions, to determine the most suitable sampling strategy and to enable standardization of the data collection in a soil sampling protocol. The study concludes that the implications of NT for the water purification and retention functions vary largely with soil type, and that some of the monitored soil properties varied more between soil types than between farming systems. The higher SOM levels under NT that increased the water retention in the soil was beneficial for soil moisture levels during the dry and warm years of monitoring, but wet soil conditions can also increase the risk of soil compaction. The elevated SOM levels also contributed to topsoil protection, along with the increased soil cover by cover crops and crop residue. This is beneficial to prevent erosion leading to soil and particulate P losses to surface waters, but the results demonstrated that the bioavailable DRP contents increased downstream the NT fields, representing important trade-offs that should be considered in soil and water management.

Both the findings from the literature review (Chapter 5 and Section 9.1) and from the monitoring case study (Chapter 6 and Section 9.2) highlight the complexity of farming systems' impacts and the importance of local soil and climatic conditions. These demonstrate that the effect of NT on the water retention and purification soil functions is highly dependent on soil texture and mineralogy, weather and other management factors, showing the risk of recommending one practice across soil types. This in turn underscores the crucial role of individual farmers' management decisions, and their understanding of the soil functions and the implications of their farming on the surrounding environment.

9.3 Farmer networks: roles and opportunities

For a better understanding of the mechanisms behind farmer management decisions more knowledge about how the implementation of NT in England is influenced by farmers' social networks is necessary. **The fourth objective** of the thesis was to provide an analysis of the NT farmers' engagement with peer networks in relation to the nature of information flow, knowledge exchange and learning between farmers (Chapter 7). Understanding these networks is particularly important as farmers often view each other as their main source of information. Furthermore, it is apparent that NT is characterised both by the need to develop situated and experiential knowledge, and to circulate this knowledge within the NT farming community in the absence of support from the advisory services.

The SNA demonstrated that farmers' social networks play a crucial role in the circulation of experiential knowledge about NT and that experienced farmers who have carried out the practice for a relatively long time are often the most influential individuals; acting as important inspirational voices. Intermediaries play an important role in enhancing knowledge and information diffusion within the network by connecting different clusters of farmers, while some farmers act as knowledge brokers by moving formal (explicit) knowledge from the science community and translating it to informal (tacit) knowledge within the farming community. NT farmers did, however, perceive themselves as having higher levels of knowledge about NT than other actors in their networks, such as researchers or external organisations, because of the farmers' practical experience with NT. Networks of NT farmers are widely distributed geographically, as the farmers often have to reach out to farmers outside their local area as they prefer to discuss NT with like-minded individuals rather than the local CT farmers.

The results further highlight the changing role of the farmers' agricultural advisers as their ability to deliver the tacit knowledge required for supporting implementation of this system is limited. This suggests a need to re-think the role of the advisers, with a suggestion that, rather than providing technical advice, they become intermediaries that connect different clusters of farmers, or knowledge network managers. They can provide validity and scientific evidence and in this way assist farmers to digest and interpret information and access institutional resources to provide digital infrastructures or act as moderators. In the future, participatory projects that are bringing relevant stakeholder together could contribute to evolving and enhancing the role of advisers while increasing knowledge integration, as discussed further in Section 9.4.1.

9.3.1 The role of social media in farmer networks

Farmer communication and knowledge exchange are essential for farmer learning and adaptation (Chapter 7 and Section 9.3), and remote communication between farmers is important for those who are geographically distributed. Therefore, understanding the interactive forms of communication within farmer networks can provide better insight into the media these networks use and, in that way, contribute further to addressing **the fourth objective** of this thesis. There is still limited information about the role of Twitter, one of the most widely used social media platforms, in learning and knowledge sharing within the farming community. The aim of Chapter 8 was to explore the potential of Twitter to drive the uptake of SSM by engaging and facilitating discussion amongst various actors, including farmers, and to explore whether it has the potential for creating a learning environment for knowledge sharing and experience exchange. To achieve this, an analysis of Tweets from the SoilCare project's Twitter account (involving16 countries) and qualitative in-depth interviews with five farmers with an active profile on Twitter was carried out to map farmer-to-farmer knowledge diffusion in relation to SSM.

Farmers in this study described Twitter as a useful platform to learn from other farmers' past experience with different practices, which was an important driver for interacting and sharing knowledge on Twitter; demonstrating the potential for farmer learning and knowledge sharing, with the advantage that it can capture the immediacy of the field operations and visual impacts of the field through photographs taken and shared in real time, and the more tacit forms of knowledge about NT. The easy accessibility of this tool was also appreciated by farmers, as they could access it from their smartphone and the short format messages were beneficial for time-constrained farmers to retrieve key information. Their connections on Twitter were mainly with peers, underscoring the findings from the SNA in Chapter 7, and the SNA interviews where farmers explained that they appreciated the feedback they received from other farmers on Twitter, highlighting the importance and potential of farmer-to-farmer learning.

Popular and respected 'farmer champions' were identified as important sources of information who would inspire fellow farmers to try new practices or techniques on their own farms, as these interactive farmers were highly respected by their fellow farmers. This concurs with SNA that different farmers take on important roles. However, the use of Twitter amongst farmers still appears to be concentrated in particular EU countries and demographics (i.e. young farmers). The five UK farmers that were interviewed in this study did, similar to the NT farmers in the SNA study, still prefer to interact and learn in a face-to-face environment but acknowledged Twitter as a useful source of additional information and inspiration for new ideas. As this technology becomes increasingly accessible for farmers (e.g. smartphones and improved internet access in rural areas), it is envisaged that the Twitter community will grow, and with this the opportunity to communicate and share knowledge across countries and continents will increase, enabling scientists and advisers to engage and interact with farmers about SSM.

In the wake of this publication, Alskaf et al. (2019) produced data that questions these results and presents conflicting findings in a study on the effects of farm and farmer characteristics on RT uptake (RT was here used as a common designation for minimum tillage and NT) in England. They concluded that social media was not an effective communication method with farmers in their study, nor a common way to inform their tillage practice decision-making.

Their study was based on a postal questionnaire (a different method from that used in Chapter 8) which provided 371 usable responses for analysis; with only two farmers practising NT, 43 farmers practising RT, and 214 practising a mix of RT and ploughing. The low number of NT respondents is one possible explanation for the differing results, indicating that there might be differences between the RT and NT farmer communities. Furthermore, the data collected for this study (described in Chapter 7 and Section 9.3) supports the conclusions that the two NT farmers involved used social media as a tool for connecting and exchanging knowledge with other farmers, especially those that were geographically distant from each other. Twitter might be more helpful to NT as a novel tillage approach as opposed to RT which is much more widespread in the UK. However, it is important to note that the recruitment of farmers for both studies in this research (Chapter 7 and 8) involved contacting farmers through social media, which might overemphasise the importance of such interactive tools in the findings from this study.

9.4 Contributions to Socio-Ecological Systems (SES)

The design of this PhD thesis called for an interdisciplinary analytical framework to explore the scientific- and farming-community's procedures for knowing and understanding soil, and how these play out at different scales. Figure 9.1 shows an adapted PhD conceptual framework integrating this analytical framework as applied in this study (modified from Figure 3.2: the PhD conceptual framework and Figure 3.1: Agriculture as a complex SES) and illustrates the key findings emerging from this project (presented in Chapter 5 to 8 and summarised in Sections 9.1 to 9.3) and the contributions from this work to the wider understanding of the complex SES.

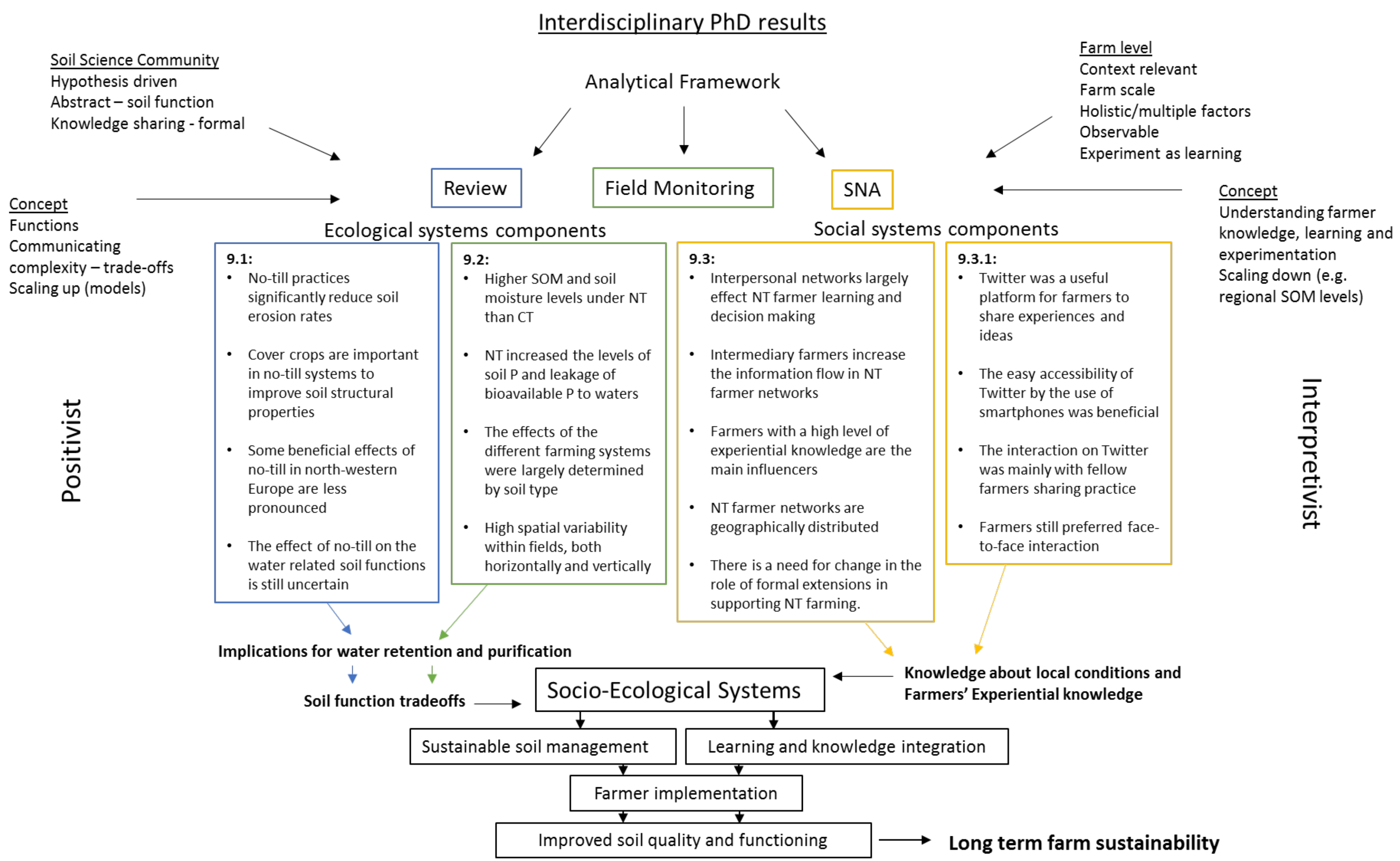

Figure 9.1. Adapted PhD conceptual framework (adapted from the Figures 3.1 and Figure 3.2) with integrated analytical framework demonstrating the key findings and how they fit into the wider SES framework.

This approach brings together the ecological and social systems component of the SES by integrating knowledge and concepts from the science (left side of Figure 9.1) and farmer communities (right side of Figure 9.1) with those from this research. Exploring socio-ecological outcomes over time is important to understanding what scenarios can lead to a more sustainable use of the system or to a resource collapse (Ostrom, 2007). Central to this framework is the idea of combining the different ways of knowing to increase the knowledge-base on sustainable soil management amongst both farmers and researchers, and to integrate the two. Section 9.4.1 will therefore assess the potential of knowledge integration in providing an improved understanding of how these communities can support each other by combining the evidence from complex scientific data with farmers' experiential knowledge, in order to reduce the gap conceptualised between formal science and farmers (Rivera-Ferre et al., 2013). This section further addresses the importance of including farmer local knowledge in research (9.4.1.1) to enhance knowledge integration, and the role of on-farm research to enable this (9.4.1.2).

Section 9.4.2 will discuss the importance of enhancing the level of knowledge about soil complexity and trade-offs between soil functions that could lead to more targeted management, as well as discussing some important challenges (as conceptualised in the SES), such as the importance of scale, trade-offs and synergies between soil functions, emerging from the PhD results.

9.4.1 Integration of knowledge from the farming and scientific community

Most NT farmers in this study did not access formal scientific information directly through scientific channels, as this was either seen as inaccessible or irrelevant (although five of the farmers in the SNA study said they accessed ten researchers all together), but accessed it indirectly in a translated format through advisers, the farming press or other channels. The field experiment setup that is often used by scientists consists of experimental designs such as a replicated randomised block design (Piepho et al., 2011) of different treatments distributed randomly across a field with reference blocks of no treatment. Farmers in the SNA study considered that such experiments do not reflect a 'real system'. As one farmer remarked "I feel disengaged with the science community because they don't see the complexity in a practical day to day system”. Their trust in research data was therefore much lower than in the experiential knowledge from their experienced peers, particularly after changing practice to NT as this was seen as a more complex system that needs local adaptation. In the context of soil, this detachment between scientists and farmers is referred to as the ‘Knowledge Paradox’ by Bouma (2010): “Research results that could potentially provide a major contribution to innovation and sustainable development are all too often not accepted by or implemented in society”.

Advisers traditionally help to fill this knowledge gap, in their role in providing advice based on scientific evidence, as well as acting as knowledge brokers between the research community and farmers. However, this relationship between the farmers and their advisers changed with the transition to NT, as those in the advisory services often had little or no experience with NT and had little access to relevant research. The results from the SNA (Chapter 7) suggested that the role of advisers needs to change, and that undertaking a network facilitation role is a potential way forward for advisory services to support innovative farmers and facilitate knowledge diffusion within information networks (Wick et al., 2018). This could contribute to more inclusive and participatory ways of integrating and sharing the knowledge needed to face the complex and locally determined challenges of agriculture (Šūmane et al., 2018, Bampa et al., 2018) and support the transition into NT farming.

Suporting farmer networks is one way of enhancing knowledge integration (Wick et al., 2018), with another being the co-generation of knowledge by farmers and scientists (Stoate et al., 2019). This has formed the basis of a number of research projects like LANDWISE, SoilCare and LANDMARK which have taken different approaches to integrating scientific and stakeholder knowledge. The LANDWISE project (funded by the UK Natural Environment Research Council) evaluates the effectiveness of land-based Natural Flood Management measures such as crop choice and tillage practices identified by people who own and manage land. By using local knowledge, the project is aiming to achieve the greatest realisable potential and is supporting people and their learning about how these measures can be used to reduce flood risk (LANDWISE, 2020). The SoilCare and LANDMARK Horizon 2020 projects both use a multi-actor approach by involving several stakeholders, including farmers, in the process. In SoilCare this participatory approach was used for selecting and evaluating soil improving cropping systems to be tested across the 16 European study sites (SoilCare, 2020), while LANDMARK assessed the sustainable management of soil in Europe including 22 partner institutes (LANDMARK, 2018). However, this can be challenging as the different ‘life worlds’ and knowledge of farmers and researchers impedes the use of scientific knowledge in practice and the integration of farmer knowledge in research (Schneider et al., 2010).

Farmers and researchers often operate on different scales, as explored in Chapter 3, with different expectations and needs from research data. This was also experienced in this PhD study as the design of the soil sampling regime in the case study (Chapter 6) needed to provide data that was seen as useful by the farmer at the same time as meeting the standards of scientific rigour required by peers, and for scientific publication. The issue of improving the interaction between science and the society was also discussed by Bouma (2010) who confirmed that there is little guidance to perform interactive research while maintaining high scientific standards. There is, however, a trend towards more participatory approaches to research in Europe (they have been used in developing countries since the 1980s) and an increased focus on combining formal and informal knowledge, both amongst policy makers and within the science communities (Šūmane et al., 2018). Such an increase will hopefully contribute to developing the methods and approaches to integrate the analytical and experiential ways of knowing and processing information by the different communities of researchers and farmers. For example, Stoate et al. (2019) used such a participatory approach by combining scientific and farmer knowledge of soil through communication, consultation and co-production of knowledge across five projects carried out in the East Midlands, UK. They concluded that different approaches to participatory research can strengthen the engagement and build trust with farming communities and enhance the understanding of how to improve soil management to both farmers and the society. This supports other studies showing that interaction between science and society is important as local farmer knowledge about soil can be more optimally used (Bouma, 2010, Crotty et al., 2019, Yageta et al., 2019, Short et al., 2019), and it is important that science engages *with* local knowledge instead of replacing it (Lyon et al., 2011, Mehring et al., 2018).

Personal communication with the case study farmers in this study after the end of the sampling period revealed that they were mostly interested in whether the practice they were implementing was considered to be effective and were seeking validation from scientific metrics but at a farm scale. Providing an answer for this based on just one study and in the context of local conditions can, however, be difficult from the perspective of the scientific method which relies on replication and uniformity in the contextual variables. The variability in values between (and within) fields of different soil types and the limited access to baseline data or knowledge about the conditions at other farms in the area make generalisations of whether the practice is beneficial, even at a farm scale, challenging. For example, comparing the SOM levels at a particular site with the UK average does not make sense as such values vary with the parent material. Although it was not possible to specify how efficient the practice was for individual farms when there is no generalised baseline to compare to, the study could still provide quantitative data on soil nutrients which are of interest to farmers, and allow a comparison between NT and CT.

9.4.1.1 Socio-ecological feedback

The complex SES of agriculture includes a combination of social and ecological processes of use, maintainance, regeneration and destruction of the soil resource (Rivera-Ferre et al., 2013, Okpara et al., 2018). These processes are affected by different variables such as farm management and the economy, soil functions and threats, potential soil degradation (both historical degradation and ongoing degradation) and both on- and off-site effects that require interdisciplinary efforts and integration of different types of knowledge to achieve sustainable solutions (Okpara et al., 2018).

The NT farmers that were interviewed in this study (Chapter 7) mentioned the lack of action from CT farmers and a 'business as usual' mindset as problematic. Some of the NT farmers said that their transition was motivated by the negative feedback signal of reduced workability of the soil[3], referring to the capability of the soil to be tilled. They expressed the opinion that continous intensive management would cause the soil quality to slowly decline to a point of depletion. This happens, for example, when components that contribute to soil feritlity are removed faster than they are replenished (Tan et al., 2005). The NT farmers described the mechanisms conceptualised as driving sustainablility in SES; the socio-ecological feedback (outlined in Chapter 3) that can lead to land use transitions. The transition occurs when depletion of the resource gives negative feedback resulting from poor management (Lambin and Meyfroidt, 2010). Feedback from arable agricultural systems might, however, only be evident when the degradation is beyond repair because of the very slow processes associated with soils.

[3] Farmers' motivations to NT implementation was not explicitly addressed in the SNA paper (Chapter 7) as there were space limitations to the paper. The data emerged from conversations and informal meetings with farmers (see table 4.4) and from question 2 in the SNA interview guide (Appendix D).

Soil structure is a slow response variable as changes in SOM stock appear slowly, as noted in Chapter 6, and negative socio-ecological feedback from, for example declining SOM content (which is closley linked to structure), would not cause rapid and critical enough changes in yield for the farmers to take the risk of changing practice, especially as the farmer could increase inputs through additional fertilizer application and still achieve acceptable results. This management strategy will, however, cause long term damage and is critical as soil is a finite resource (FAO and ITPS, 2015a). Therefore, the challenge of achieving long-term soil sustainability, which is the goal of the SES framework, in this type of resource system, where visible negative feedback signals are absent, requires additional efforts. The slow soil response means that once higher SOM is achieved it can be sustained and farmers are now starting to valuate the long-term resilience this provides. Participatory approaches to integrating local experiential farmer knowledge in research is important so that the different social and ecological dimension of the SES are accounted for. For example, Lehébel-Péron et al. (2016), successfully used a participatory approach to combine scientific and traditional knowledge to rehabilitate dramatically declining heather honey production in Southern France. This was a typical example of 'socio-ecologic feedback' where the knowledge of stakeholders such as local beekeepers, specialists of heather and researchers was combined and utilized to fully understand the various drivers of change; including climatic, socio-economic and ecological factors that all interconnect and should be assessed together. Similarly, the information provided by the NT farmers in this study has been integrated with the scientific monitoring data to contribute to a wider understanding of the system.

9.4.1.2 Farmer knowledge and learning

The importance of considering farmer knowledge about field conditions and soil properties when evaluating the effects of different farming practices or when designing on-farm soil research was highlighted in the UK monitoring case study (Chapter 6). The results from the interviews in Chapter 7 showed that it takes time for farmers to build up this experience for understanding how to carry out a new practice successfully. The NT farmers in the SNA study would watch more experienced farmers and follow the unofficial "rules of NT" the first few years after changing practice. Eventually, they would start experimenting on their own farm and build experiential knowledge of their own. Once they had more experience and confidence they would adapt the practice to suit their particular farm conditions (Chapters 7 and 8). This way farmers could improve their understanding of the basis of why elements of the farming procedure worked so that they would know what to change if it stopped working (Lyon et al., 2011). These observations are supported by a number of studies of farmers' experiential learning (Nuthall and Old, 2018, Martin, 2015, Sewell et al., 2014), and are of particular relevance to the transition from CT to non-inversion systems.

The experimentation and development of their own site specific knowledge was particularly important after implementing NT as they could no longer just rely on their advisers (Ingram, 2010, Milestad et al., 2010, Samiee and Rezaei-Moghaddam, 2017); nor apply "recipe farming" (Lyon et al., 2011) in which farmers follow prescriptive formulas from agricultural science (Lyon et al., 2011, Leeuwis and Van den Ban, 2004). It has been argued that linear agricultural processes have not been able to consider the needs of a particular local environment, but rather create a dependency on uniform external knowledge sources (Šūmane et al., 2018, Leeuwis and Van den Ban, 2004). Lyon et al. (2011) tried to understand how agricultural science could ovecome this and move towards embracing the variability of different geographical contexts. They desribe the key challenge as the conflict between the principles of science and the experience of the farmers, as the scientific community often seek knowledge that has a wider impact and can be generalized across time and space (or 'scaled up' as shown in Figure 9.1), whereas farmers are more concerned with what works at the field-scale level.

9.4.1.3 On-farm research

Undertaking on-farm research (as reported in Chapter 6) is one potential way of moving the agricultural sciences towards embracing the heterogeneity of space found on farmers' fields. On-farm research is believed to have a beneficial effect on generating new or modified technologies, as it allows the researcher to have an appreciation of farm conditions and challenges, for researchers and farmers to share observations, and for researchers to draw on the farmer's practical experience (Moayedi and Azizi, 2012). However, although farmers are experienced, they might lack the ability to interpret in-depth scientific information that is essential to successfully carrying out new and perhaps more complex farming practices (Ingram, 2008). Examples of this are understanding about the different trade-offs, off-site effects or below ground processes resulting from different management, that are not directly visible for the farmer (this is discussed further in Section 9.4.2).

The case study reported in Chapter 6 revealed the complex interactions between SOM, soil saturation and the N cycle, that would be difficult for the farmer to observe. This on-farm approach to research could therefore improve farmers' understandings of the mechanisms behind the topsoil and above ground results they are viewing as the research findings are communicated back to them. Meetings with the case study farmers in this study were therefore arranged towards the end of the project to discuss the findings with them, benefiting the farmers as findings and patterns from their fields were explained, and benefiting the project as the farmers provided their views on these findings. Research that is carried out on farmers' fields and in a farming environment is a good starting point for designing suitable and relevant research for local conditions (Moayedi and Azizi, 2012).

Similarly, advisory and extension recommendations derived from research are only relevant to farmers if they take the varying soil characteristics of fields and environmental factors of the farm into account, as explored in Chapter 6. Therefore, research and advice/extension need to make better use of farmer knowledge by working closely together and offering flexible soil management options that the farmers can fine-tune to meet their specific site conditions. Such an approach needs a co-design (participatory) research design which could contribute to establishing relationships of trust and help to encourage farmers to enhance their soil resources (Skaalsveen et al., 2020, Poncet et al., 2010). Furthermore, such an approach will lead to an improvement of the "know-how" of farmers so that they will be better equipped to examine their soils and interpret what they see, in addition to improved "know-why" which offers a scientiifc understanding of cause and effect mechanisms from formal scientific knowledge (Ingram, 2008), important to successfully carrying out a complex practice like NT.

9.4.2 Soil function complexity and trade-offs

Strengthening of the "know-why" of both farmers and researchers is important to improve understanding of the variability in responses to the different soil types and climatic conditions (as discussed in Chapters 5 and 6), but also to provide an overview of the trade-offs that might occur between all soil functions (or for separate functions, as explored in this study) under different conditions (Schulte et al., 2014, O'Sullivan et al., 2015, Valujeva et al., 2016). The complexity of soil processes was explored in Chapter 5 and 6, which assessed the effect of NT farming on the water related soil functions. Important scientific arguments for introducing NT systems are the beneficial effects for erosion reduction (Schoumans et al., 2014, Mhazo et al., 2016, Gaiser et al., 2008, Vogel et al., 2016, Todorovic et al., 2014), improving habitats for biodiversity (Bertrand et al., 2015, Crotty et al., 2016) and enhancing C levels in the topsoil (Oorts et al., 2006, Hazarika et al., 2009, Ulrich et al., 2006). These effects do, however, vary greatly with soil type and climate; in some cases the transition to this system lead to negative impacts, such as increased DRP leaching (with potentially high impact on water quality) (demonstrated in Chapter 6) and increased fluxes of N-gasses (Soane et al., 2012). Other studies have, however, discovered a higher number of potential trade-offs between soil functions under CT than under NT (Frank et al., 2014, Tamburini et al., 2016, Stavi et al., 2016). Such trade-offs both between all soil functions and for the separate functions need to be considered to ensure that the optimal measure or practice is implemented (O'Sullivan et al., 2018, Bouma, 2014), as soils have a different capability to deliver each of the different soil functions (Schulte et al., 2014, Haygarth and Ritz, 2009, Glæsner et al., 2014). Figure 9.2 summarises these different findings.

This study has provided analytic evidence by assessing the water retention and purification function under different soil and management conditions. To date, there are few similar studies assessing soil functions (O'Sullivan et al., 2015, Valujeva et al., 2016). More has been done on the synergies between different ESS as the interactions between the services are important to understand the implications of developing policy and economic incentives for the promotion of particular ESS (Smith et al., 2013). A central reason for this is that environmental and agricultural policies are increasingly outlined on the basis of ESS (O'Sullivan et al., 2018), such as the ‘payments for ecosystem services scheme’ (Arnott et al., 2019) as noted in Chapter 2. Although the ESS are on a ‘higher organisational level’ than the soil functions, soils have a crucial role in delivering ecosystem goods (as described in Chapter 3) and the same challenges arise in terms of cross-linkages between services or functions, resulting from many different physical and chemical components that are subject to a range of environmental drivers (Smith et al., 2013). More knowledge about the soil function complexity is therefore important in developing future legislation and successful outcomes from initiatives such as those that offer ‘payments for ecosystem services ’, but also to place more emphasis on synergies. An example is the current absence of policies addressing both soil and water in the UK (explored in Chapter 2) although healthy and functioning soils are crucial for good water management.

This was also demonstrated by this study as the NT practice that was aiming to improve soil properties connected to the particular function of water retention and purification (such as erosion mitigation) can provide co-benefits (as erosion mitigation led to increased topsoil SOM and reduced suspended sediments in downstream waters), but also result in trade-offs (by increasing nutrient leaching from the plant material that is covering and protecting the soil to downstream waters) as observed by others (Stavi et al., 2016, Valujeva et al., 2016, Schulte et al., 2015, Robinson et al., 2013, Smith et al., 2015, Smith et al., 2013, Lindborg et al., 2017). More emphasis should be placed on managing and maintaining integrated soil functions as they are necessary to support different ESS (Drobnik et al., 2018, Robinson et al., 2013) Smith et al. (2013) therefore called for an ESS framework to address co-benefits and trade-offs for improved coordination of ecosystem management. Similarly, such a framework for the soil functions, taking different local conditions into account, was recommended by Schulte et al. (2014) who developed the FLM framework (see Chapter 3). Although the framework represented an important step towards the quantification of the 'supply of' and 'demand for' soil functions, their analysis did not assess the potential interactions between soil functions. Central to this framework is the realization that some soils perform particular functions better than others as demonstrated by the particularly beneficial effects of NT under Cotswold brash soil reported in Chapter 6. However, Valujeva et al. (2016) argues that the aim of soil management should be to optimise rather than maximise the supply of each function.

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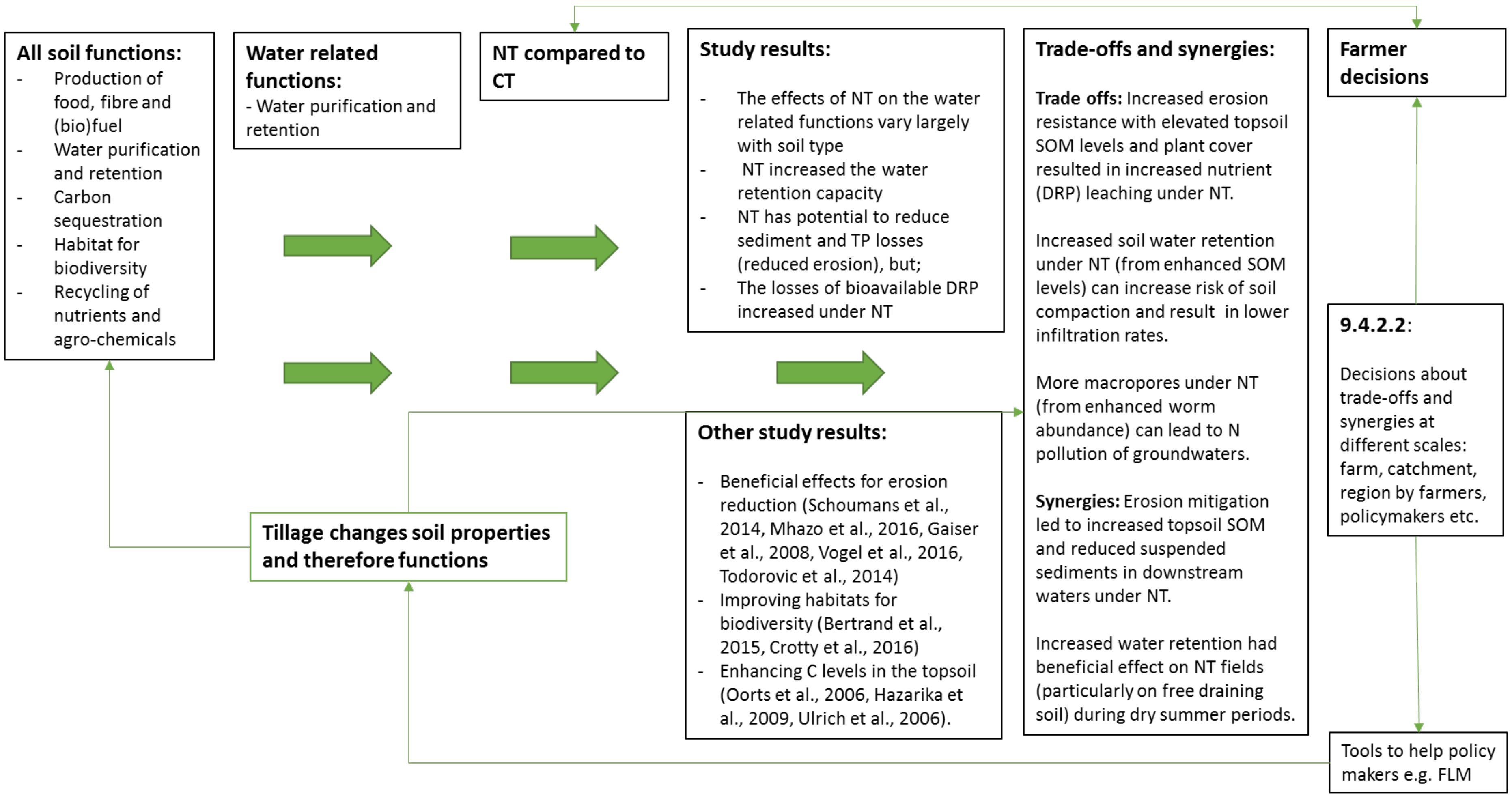

Figure 9.2. Summary chart illustrating the findings from this and other studies in the context of trade-offs, synergies and farmer decisions.

9.4.2.1 Spatial variability in function delivery

The importance of soil type and landscape for delivering soil functions was outlined earlier in this chapter, but the co-benefits and trade-offs between soil functions are also largely affected by the combination of the soil type and the soil management system applied by the farmer. This was demonstrated by the findings in Chapter 6 (summarised in section 9.2 and Figure 9.1) that show the varying effect of NT and CT practices on a free-draining porous limestone soil and a lime-rich loamy soil. Understanding the multi-functionality of soils as a function of land use and soil type are important steps towards improved soil management (Tamburini et al., 2016). This PhD study also concludes that assessing local variations of soil type and accounting for the best possible functionality of different combinations of soil type and land management is important (Schulte et al., 2014, Haygarth and Ritz, 2009). Undertaking a regional approach was also advised by Lindborg et al. (2017) who suggested that trade-offs and synergies vary with scale and that managing them would be easier at larger scales, such as the landscape or regional scale, as the scale of management should match the scale of the processes behind ESS generation.

This study assessed the two systems of NT and CT, representing low and high intensity tillage systems, but only focusing on one of the soil functions (Chapter 6). Other studies have undertaken modelling or review approaches to predict the trade-offs between several functions or services (Stavi et al., 2016, Tian et al., 2016, Valujeva et al., 2016, Yang et al., 2019, O'Sullivan et al., 2015, Frank et al., 2014). A conceptual model developed to compare soil functions and ESS between agricultural systems was developed by Stavi et al. (2016), illustrated in Figure 9.3. The authors acknowledged that site-specific and local conditions could have altered these scores, hence producing generalized results that might differ between geographical areas. The figure shows that the water availability and erosion control are shown as high under conservation, which mirrors findings from Chapter 6 under NT, while similarities to the high soil quality score in Figure 9.3 are dependent on what variable is used to describe this. Facing these trade-offs associated with different farming practices is, however, important as they are key to understanding the benefits to this farming system (Tamburini et al., 2016).

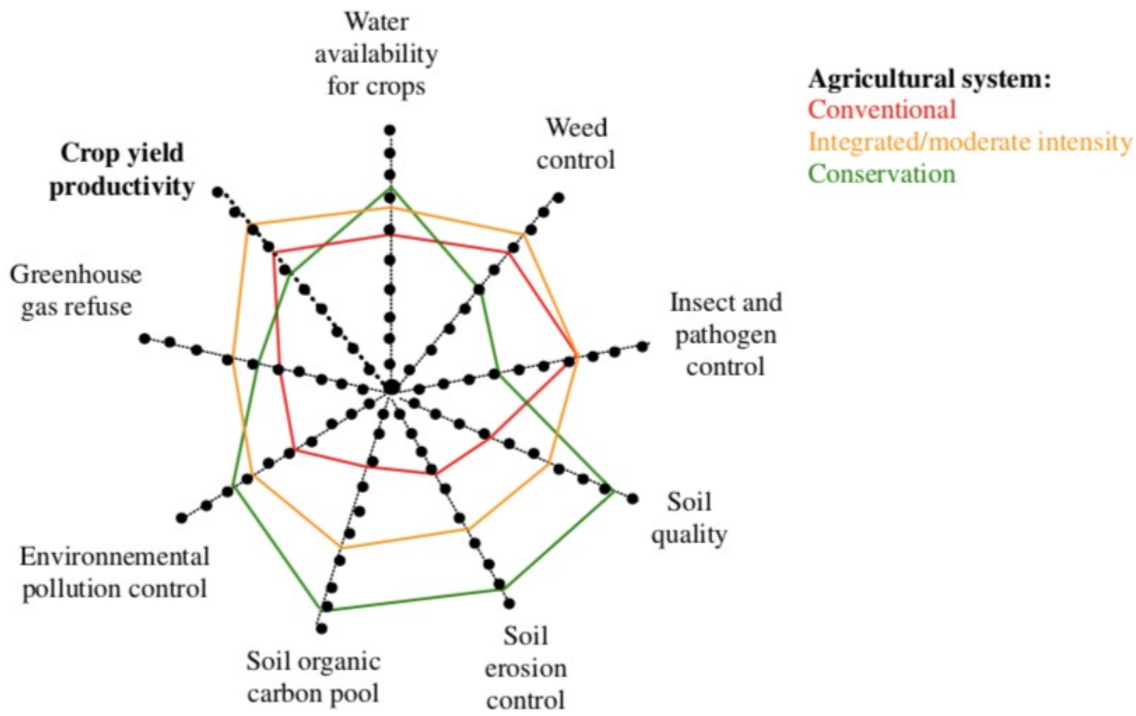

Figure 9.3. The scores per agricultural system per soil function/ESS illustrating the potential trade-offs between them (source: Stavi et al., (2016)).

9.4.2.2 Soil functions on different scales

As noted in earlier sections, the water purification and retention functions assessed in this PhD study (Chapter 6) were only partially impacting the farmer, for example while soil moisture content is important, other impacts such as the changes in downstream water quality represent an off-site effect that was less noticeable for the farmer. Farmers in this study (from the SNA) were, however, interested in improving soil properties that could indirectly benefit this soil function; for example by increasing SOM levels (highly correlated with soil moisture storage), to protect their soils from erosion (less sediment and particulate P inputs to waters), enhancing soil structure, fertility and cover with cover crops (can increase N uptake and prevent leaching), and increase soil biodiversity (vertically drilling worms are providing macropores that increase water storage and infiltration, while micro biodiversity is beneficial for water filtering and 'cleansing'). The demand for such functions operate on different scales (Schwilch et al., 2016); for example, water purification manifests itself at the local scale and water retention at the catchment scale, while the demand for greenhouse gas mitigation primarily exists on a national scale (Valujeva et al., 2016, Schulte et al., 2015). The mismatch between scales, both temporally and spatially, in the supply and demand for functions can also challenge optimal management strategies (Valujeva et al., 2016, O'Sullivan et al., 2018). Understanding the priorities of the people who are supplying (e.g. primarily farmers and foresters) and demanding (e.g. policy makers) soil functions is essential to understanding how the separate functions are prioritised by these different actors, and there is a current gap between the two (O'Sullivan et al., 2015, O'Sullivan et al., 2018).

Farmers in this study had to place emphasis on their yields (providing the farm income) as they were running a business, but would often accept lower yields, particularly the first years after implementation of NT, as they wished to enhance other soil functions. The divergence of prioritisation of soil functions calls for efforts to harmonise and incentivise (or suppress) the delivery of such soil functions. Development of agri-environmental policies that can tackle such trade-offs between functions on different scales is important, and to assess the opportunities and synergies between national and local target setting so that the two can be better connected. Engaging a wide range of stakeholders, as discussed in the earlier sections of this chapter, adds complexity. Nevertheless, as exemplified in this PhD study and outlined by the SES framework, cooperation between diverse stakeholders and different disciplines of science is crucial in achieving multiple objectives from the soil resource (O'Sullivan et al., 2018).

9.5 Limitations of the study

9.5.1 Field monitoring

In assessing the water purification function of the soil under different farming systems, the field monitoring of this study did not include the soils' ability to filter pesticides. Pesticides are important to NT farmers for weed suppression (as they are not inverting the soil) (Tørresen et al., 2003; Soane et al., 2012). Other additional variables such as assessments of water percolation through deep vertical macropores from vertically drilling earthworms, groundwater quality (for monitoring of harmful N leaching), hydraulic conductivity (in addition to the infiltration tests), water holding capacity and aggregate stability would also have added value to the discussion of the suitability of NT for improving the water related soil functions. The decision to exclude these analyses was based on the limited scope of the study and the lack of facilities to carry out these analyses. In hindsight, a more thorough assessment of water quality elements (such as suspended solids, total N and NO_3^-) would have been beneficial for improving evaluations of the effect of NT on the water purification function. An early attempt to use SONDES equipment was hampered by a technical fault and unfortunately this could not be fixed or replaced.

Inevitably a short study imposes a number of limitations in terms of allowing sufficient time for meaningful changes to result from systems' changes. Furthermore, the weather conditions (in particular the summer drought conditions during the study period) affected the sediment trap data collection and sampling from the waterways.

A limitation to the case study design is the uncertainty resulting from comparing a small number of fields instead of, for example, carrying out a randomized block design with several replications. Assessing commercial farming systems that do not enable control of the field operations results in a large number of 'unknowns' in terms of removing/controlling some variables, particularly with limited baseline data to compare with. Approaches that allow monitoring of real farming operations, but with some comparative ability, are a consideration for future research. The initial assumption that the two farms had sufficiently similar soil types to allow a fair comparison between systems was also a limitation (although the soil analysis performed during the project confirmed they were similar). Ideally, a longitudinal study that captures baseline data is a better approach than comparing farms of 'similar' soil type.

9.5.2 Farmer interviews

The SNA approach was useful to map farmers' social networks, but a limitation of the SNA study was that the interviewees were limited to farmers. Some of the main conclusions emerging from the SNA were that advisers need to undertake a new role to support innovative farmers, and that farmers tend to trust shared experiential knowledge more than formal scientific information. The opportunity to triangulate this with interviews with advisers and researchers would have added depth and insight to the discussion, and potentially have revealed a different or more nuanced picture. The discussion and conclusions in this study are largely informed by talking to farmers (both those in the SNA and Twitter studies and the case study farmers) about the science and farmer communities, and the need for integration. This observation supports a common theme in the literature, however I acknowledge that there are limitations in drawing these conclusions without talking to scientists themselves.

The numbers of farmers and recruitment of these farmers were further limitations to both the SNA (n = 16) and Twitter (n = 5) papers. The farmer interviews for the Twitter paper were intended to enhance the Twitter content analysis and as such the results are indicative only. A higher number of farmers could have strengthened the SNA study as more evidence is needed to fully understand the dynamics and characteristics of NT farmer networks, and confirm the patterns observed, but this was not possible within the time available in this PhD study. The interviews were only carried out once, although interviewing the SNA NT farmers before and after implementation would have been beneficial to assess the temporal changes to these networks. The SNA study was limited to mapping the current ego-networks of the participants and recruiting more farmers by the snowball approach, potentially overemphasising the connections within the network. Recruiting some of the farmers from both the SNA and Twitter paper through Twitter can also overemphasize the role of social media for NT farmer communication, and biases the SNA sample on a certain type of NT farmer (i.e. it may not have adequately captured the NT farmers who are not on Twitter who have different sorts of social networks). However, early attempts to identify NT farmers through local networks (i.e. the Farming and Wildlife Advisory Group), email or telephone, originally focusing on the catchment where the case study monitoring took place, did not reveal any willing respondents.

This chapter has provided a presentation of the results from the four main Chapters of this thesis (paper Chapters 5-8) and discussed the findings in light of other relevant scientific literature. Following on from this, the Conclusion Chapter will provide a brief summary of the key findings from this study and end with the recommendations for future research.

10 Conclusion

By undertaking an interdisciplinary research design, monitoring the field scale effects of different farming systems on the water related soil function and investigating the social dynamics of the networks that are affecting farmers' decisions about implementing such systems, this PhD study provides an original contribution to knowledge. The social and natural systems components were tied together by a complex SES framework aiming to integrate knowledge and concepts from both science and farmer knowledge.

Findings from this study demonstrate that there are still uncertainties regarding the effects of NT in NW Europe and results from the case study showed the great variations that exist both within and between fields under the same agricultural system. There were often larger differences in soil variables attributable to soil types than to farming system. This highlights the heterogeneity of soils and the potential trade-offs and synergies that can result from different combinations of soil types, management practices, human factors and weather conditions. The on-farm research approach that was undertaken in this study has potential to support and validate experiential learning. The monitoring phase of the research provided evidence that was not directly visible to the case study farmers, such as the complex interactions between SOM, soil saturation and the N cycle processes, while information and views from the farmers that was provided during the interim and post-study meetings was helpful when interpreting some of these results. Results from this study also demonstrated the crucial role of the social networks of NT farmers for decision-making and learning. Understanding of how farmer knowledge is produced and circulated within these networks is important to advisers for providing support to innovative farmers. Supporting farmer networks with scientific input could contribute to more inclusive and participatory knowledge integration and co-generation of knowledge by farmers and scientists, producing data to meet expectations and standards from both communities.

Findings from this study represent important inputs to the ongoing discussion of the future environmental land management policy and related schemes of the UK. The findings demonstrate the importance of participation and integration of different knowledge types for achieving sustainable soil management, that local variations in soil and field types can determine the outcome of different management strategies, and the need for more effective and targeted advisory services. Moving away from EU's CAP the UK has a unique opportunity to redesign the Environmental Land Management policies and develop less prescriptive schemes allowing farmers to participate in the process of selecting the measures that will benefit their soils the most while addressing local environmental challenges. The trade-offs between soil functions that were discussed in this thesis represent an important challenge to the suggested strategies where farmers are payed for providing public goods. This is underpinning the importance of local knowledge as the supply and demand for the different public goods will vary between areas and that a "local prioritisation" will be necessary.

10.1 Recommendations for future research

This study demonstrates that predicting the total impact of farming system change on soil functions is a challenging task as several soil chemical, physical and biological processes interplay and vary with local conditions and human factors. The importance of knowledge integration between different actors of a SES was discussed in Chapter 9. In particular, integration of knowledge between actors of the different disciplines of soil science (e.g. soil biodiversity, soil chemistry, soil physics etc.) is recommended to provide a better understanding of the soil system responses in an agricultural ecosystem context, optimising the multifunctional use of soils. This study contributes by revealing some of this complexity by assessing separate soil functions under different soil conditions, but future research would benefit from taking a wider scope and aiming to monitor all soil functions in a similar site-specific way (and under different management systems) for more knowledge about trade-offs and synergies.

There is a lack of a widely accepted measure or metrics for soil functions, which is a substantial barrier for effectively communicating with actors outside the soil science community. In this study, this was identified when conducting the literature review (Chapter 5), as both the variables measured and the units used to monitor these were not consistent. It was also identified in the case study (Chapter 6) where, for example the variability in the number and depth of soil samples was shown to have large implications for the results (making direct comparisons with other studies difficult). The monitoring methods should therefore be standardized with common function indicators, so that these types of studies would be more comparable.

An example of such an indicator is one to monitor the SOM/SOC stocks that are generally depleted in agricultural systems compared to natural ecosystems. A decline in the SOM/SOC concentration is likely to affect the delivery of soil functions as SOM plays a significant, but complex, role in underpinning many of the soils' functional properties (Haygarth and Ritz, 2009, Villarino et al., 2019). This study, therefore, undertook a thorough monitoring of SOM in the case study fields (Chapter 6). The levels of SOM often vary largely between regions depending on the soil parent material and historical management. Therefore, benchmarking the SOM/SOC levels (and other important indicators) for different farming regions would be a useful way to create a baseline for farmers and researchers, particularly for shorter projects that are unable to collect longitudinal data.

Results from this study show that NT is promising for SOM conservation and for reducing soil losses in the UK, which is important for long-term soil sustainability. The assessments of policies with impact on soil protection and conservation in the UK and England (Chapter 2) indicate that the current legislative action is not adequate. The positive experiences and activities of the NT farmers and their networks in this study, however, suggest that voluntary efforts by such farmer communities should be encouraged to foster a higher uptake of this management, where appropriate. Current participatory initiatives such as the Countryside Stewardship Facilitation Fund farmer groups, Innovative Farmers, and AHDB Monitor Farms could serve as a model for formalising such an approach. The opportunity to pay farmers for public goods in the forthcoming ELMs individually or in groups will also be a way of achieving this by incentivising practices that deliver selected soil functions.

References

ABDOLLAHI, L., MUNKHOLM, L. J. & GARBOUT, A. 2014. Tillage System and Cover Crop Effects on Soil Quality: II. Pore Characteristics. *Soil Science Society of America Journal,* 78.

ALSKAF, K., SPARKES, D. L., MOONEY, S. J., SJÖGERSTEN, S. & WILSON, P. 2019. The uptake of different tillage practices in England. *Soil Use and Management*.

ARMAND, R., BOCKSTALLER, C., AUZET, A. & VANDIJK, P. 2009. Runoff generation related to intra-field soil surface characteristics variabilityApplication to conservation tillage context. *Soil and Tillage Research,* 102**,** 27-37.

ARNOTT, D., CHADWICK, D., HARRIS, I., KOJ, A. & JONES, A. 2019. What can management option uptake tell us about ecosystem services delivery through agri-environment schemes? *Land Use Policy,* 81**,** 194-208.

ARONSSON, H., HANSEN, E. M., THOMSEN, I. K., LIU, J., ØGAARD, A. F., KÄNKÄNEN, H. & ULEN, B. 2016. The ability of cover crops to reduce nitrogen and phosphorus losses from arable land in southern Scandinavia and Finland. *Journal of Soil and Water Conservation,* 71**,** 41-55.

ASKARI, M. S., CUI, J. & HOLDEN, N. M. 2013. The visual evaluation of soil structure under arable management. *Soil and Tillage Research,* 134**,** 1-10.

AUTRET, B., BEAUDOIN, N., RAKOTOVOLOLONA, L., BERTRAND, M., GRANDEAU, G., GRÉHAN, E., FERCHAUD, F. & MARY, B. 2019. Can alternative cropping systems mitigate nitrogen losses and improve GHG balance? Results from a 19-yr experiment in Northern France. *Geoderma,* 342**,** 20-33.

BAARS, T. 2010. Experiential Science; Towards an Integration of Implicit and Reflected Practitioner-Expert Knowledge in the Scientific Development of Organic Farming. *Journal of Agricultural and Environmental Ethics,* 24**,** 601-628.

BAILEY, A., DEASY, C., QUINTON, J., SILGRAM, M., JACKSON, B. & STEVENS, C. 2013. Determining the cost of in-field mitigation options to reduce sediment and phosphorus loss. *Land Use Policy,* 30**,** 234-242.

BAIRD, J., JOLLINEAU, M., PLUMMER, R. & VALENTI, J. 2016. Exploring agricultural advice networks, beneficial management practices and water quality on the landscape: A geospatial social-ecological systems analysis. *Land Use Policy,* 51**,** 236-243.

BALESDENT, J., CHENU, C. & BALABANE, M. 2000. Relationship of soil organic matter dynamics to physical protection and tillage. *Soil and tillage research,* 53**,** 215-230.

BAMPA, F., O'SULLIVAN, L., MADENA, K., SANDÉN, T., SPIEGEL, H., HENRIKSEN, C. B., GHALEY, B. B., JONES, A., STAES, J., STUREL, S., TRAJANOV, A., CREAMER, R. E. & DEBELJAK, M. 2018. Harvesting European knowledge on soil functions and land management using multi- criteria decision analysis. *Soil Use and Management,* 35**,** 6-20.

BANDURA, A. 1977. Self-efficacy: Toward a unifying theory of behavioral change. *Psychological Review,* 84**,** 122-147.

BARTOLINI, F., GALLERANI, V., RAGGI, M. & VIAGGI, D. 2012. Modelling the Linkages between Cross-Compliance and Agri-Environmental Schemes Under Asymmetric Information. *Journal of Agricultural Economics,* 63**,** 310-330.

BASCH, G., KASSAM, A. & GONZÁLEZ-SÁNCHEZ, E. 2017. Sustainable Soil Management: Its perception and the need for policy intervention. *Paper presented at the EGU General Assembly Conference Abstracts*.

BAUMGART-GETZ, A., PROKOPY, L. S. & FLORESS, K. 2012. Why farmers adopt best management practice in the United States: a meta-analysis of the adoption literature. *J Environ Manage,* 96**,** 17-25.

BAVEYE, P. C., BAVEYE, J. & GOWDY, J. 2016. Soil "Ecosystem" Services and Natural Capital: Critical Appraisal of Research on Uncertain Ground. *Frontiers in Environmental Science,* 4.

BECHMANN, M., DEELSTRA, J., STÅLNACKE, P., EGGESTAD, H. O., ØYGARDEN, L. & PENGERUD, A. 2008. Monitoring catchment scale agricultural pollution in Norway: policy instruments, implementation of mitigation methods and trends in nutrient and sediment losses. *Environmental Science & Policy,* 11**,** 102-114.

BEHRENDS KRAEMER, F., HALLETT, P. D., MORRÁS, H., GARIBALDI, L., COSENTINO, D., DUVAL, M. & GALANTINI, J. 2019. Soil stabilisation by water repellency under no-till management for soils with contrasting mineralogy and carbon quality. *Geoderma,* 355.

BELLAMY, P. H., LOVELAND, P. J., BRADLEY, R. I., LARK, R. M. & KIRK, G. J. 2005. Carbon losses from all soils across England and Wales 1978-2003. *Nature,* 437**,** 245-8.

BELLOTTI, B. & ROCHECOUSTE, J. F. 2014. The development of Conservation Agriculture in Australia—Farmers as innovators. *International Soil and Water Conservation Research,* 2**,** 21-34.

BENNETT, E. M., CARPENTER, S. R. & CARACO, N. F. 2001. Human Impact on Erodable Phosphorus and Eutrophication: A Global Perspective. *Bioscience,* 51**,** 227-234.

BERENDSE, D. C., KLEIJN, D. & SCHEKKEMAN, H. 2004. Declining Biodiversity in Agricultural Landscapes and the Effectiveness of Agri-Environment Schemes. *Ambio,* 33**,** 499-502.

BERGSTROM, L., KIRCHMANN, H., DJODJIC, F., KYLLMAR, K., ULEN, B., LIU, J., ANDERSSON, H., ARONSSON, H., BORJESSON, G., KYNKAANNIEMI, P., SVANBACK, A. & VILLA, A. 2015. Turnover and losses of phosphorus in Swedish agricultural soils: long-term changes, leaching trends, and mitigation measures. *J Environ Qual,* 44**,** 512-23.

BERKHOUT, F. 2006. Normative expectations in systems innovation. *Technology Analysis & Strategic Management,* 18**,** 299-311.

BERTRAND, M., BAROT, S., BLOUIN, M., WHALEN, J., DE OLIVEIRA, T. & ROGER-ESTRADE, J. 2015. Earthworm services for cropping systems. A review. *Agronomy for Sustainable Development,* 35**,** 553-567.

BODIN, Ö. & TENGÖ, M. 2012. Disentangling intangible social–ecological systems. *Global Environmental Change,* 22**,** 430-439.

BODNER, G., HIMMELBAUER, M., LOISKANDL, W. & KAUL, H. P. 2010. Improved evaluation of cover crop species by growth and root factors. *Agronomy for Sustainable Development,* 30**,** 455-464.

BODNER, G., LOISKANDL, W., BUCHAN, G. & KAUL, H. P. 2008. Natural and management-induced dynamics of hydraulic conductivity along a cover-cropped field slope. *Geoderma,* 146**,** 317-325.

BODNER, G., LOISKANDL, W. & KAUL, H. P. 2007. Cover crop evapotranspiration under semi-arid conditions using FAO dual crop coefficient method with water stress compensation. *Agricultural Water Management,* 93**,** 85-98.

BODNER, G., SCHOLL, P., LOISKANDL, W. & KAUL, H. P. 2013. Environmental and management influences on temporal variability of near saturated soil hydraulic properties. *Geoderma,* 204-205**,** 120-129.

BORGATTI, S. P. & HALGIN, D. S. 2011. On Network Theory. *Organization Science,* 22**,** 1168-1181.

BOS, E & OWEN, L. 2016. Virtual reconnection: The online spaces of alternative food networks in England. *Journal of rural studies*, 45, 1-14.

BOUMA, J. 2010. Implications of the Knowledge Paradox for Soil Science. *Advances in Agronomy v106.*

BOUMA, J. 2014. Soil science contributions towards Sustainable Development Goals and their implementation: linking soil functions with ecosystem services. *Journal of Plant Nutrition and Soil Science,* 177**,** 111-120.

BOUMA, J., DE VOS, J. A., SONNEVELD, M. P. W., HEUVELINK, G. B. M. & STOORVOGEL, J. J. 2008. The Role of Scientists in Multiscale Land Use Analysis: Lessons Learned from Dutch Communities of Practice. *Advances in Agronomy Volume 97.*

BOURNE, M., GASSNER, A., MAKUI, P., MULLER, A. & MURIUKI, J. 2017. A network perspective filling a gap in assessment of agricultural advisory system performance. *Journal of Rural Studies,* 50**,** 30-44.

BRITISH GEOLOGICAL SURVEY 2018. Regional geological summaries. Central England region (version 2). *https://www.bgs.ac.uk/research/ukgeology/regionalGeology/home.html*.

BRONICK, C. J. & LAL, R. 2005. Soil structure and management: a review. *Geoderma,* 124**,** 3-22.

BROOKER, R. W., BENNETT, A. E., CONG, W. F., DANIELL, T. J., GEORGE, T. S., HALLETT, P. D., HAWES, C., IANNETTA, P. P. M., JONES, H. G. & KARLEY, A. J. 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytologist,* 206**,** 107-117.

BROWN, J. S. & DUGUID, P. 2001. Knowledge and Organization: A Social-Practice Perspective. *Organization Science 12,* 12**,** 198-213.

BRUNORI, G., BARJOLLE, D., DOCKES, A., HELMLE, S., INGRAM, J., KLERKX, L., MOSCHITZ, H., NEMES, G. & TISENKOPFS, T. 2013. CAP reform and innovation: the role of learning and innovation networks. *Eurochoices,* 12**,** 27-33.

BUCZKO, U., BENS, O., HANGEN, E., BRUNOTTE, J. & HÜTTL, R. F. 2003. Infiltration and macroporosity of a silt loam under two contrasting tillage systems. *Landbauforschung Volkenrode,* 53**,** 181-190.

BURR-HERSEY, J. E., MOONEY, S. J., BENGOUGH, A. G., MAIRHOFER, S. & RITZ, K. 2017. Developmental morphology of cover crop species exhibit contrasting behaviour to changes in soil bulk density, revealed by X-ray computed tomography. *PLoS One,* 12**,** e0181872.

BURTON, R., DWYER, J., BLACKSTOCK, K., INGRAM, J., BROWN, K., MILLS, J., SCHWARZ, G., MATHEWS, K. & SLEE, B. 2007. Influencing positive environmental behaviour among farmers and landowners-a literature review. *Report to DEFRA. Socio-Economic Research Group, The Macaulay Land Use Research Institute*.

BUSARI, M. A., KUKAL, S. S., KAUR, A., BHATT, R. & DULAZI, A. A. 2015. Conservation tillage impacts on soil, crop and the environment. *International Soil and Water Conservation Research,* 3**,** 119-129.

CADGER, K., QUAICOO, A., DAWOE, E. & ISAAC, M. 2016. Development Interventions and Agriculture Adaptation: A Social Network Analysis of Farmer Knowledge Transfer in Ghana. *Agriculture,* 6.

CAMPBELL, L. M. 2005. Overcoming Obstacles to Interdisciplinary Research. *Conservation Biology,* 19**,** 574-577.

CANNELL, R. Q., DAVIES, D. B., MACKNEY, D. & PIDGEON, J. D. 1978. The suitability of soils for sequential direct drilling of combine-harvested crops in Britain: a provisional classification. *Outlook Agric,* 9**,** 306-316.

CAPOWIEZ, Y., CADOUX, S., BOUCHANT, P., RUY, S., ROGER-ESTRADE, J., RICHARD, G. & BOIZARD, H. 2009. The effect of tillage type and cropping system on earthworm communities, macroporosity and water infiltration. *Soil and Tillage Research,* 105**,** 209-216.

CAROLAN, M. S. 2006. Social Change and the Adoption and Adaptation of Knowledge Claims: Whose Truth Do You Trust in Regard to Sustainable Agriculture? *Agriculture and Human Values*.

CARPENTER, S. R., CARACO, N. F., CORELL, D. L., HOWART, R. W., SHARPLEY, A. N. & SMITH, V. H. 1998. Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen. *Ecological Applications,* 8**,** 559-568.

CARTER, M. R. 1987. Physical properties of some Prince Edward Island soils in relation to their tillage requirement and suitability for direct drilling. *Can. J. Soil Sci*., 672 473-487.

CERF, M., BAIL, L., LUSSON, J. M. & OMON, B. 2017. Contrasting intermediation practices in various advisory service networks in the case of the French Ecophyto plan. *The Journal of Agricultural Education and Extension,* 23**,** 231-244.

CHAMBERS, R. & JIGGINS, J. 1987. Agricultural research for resource-poor farmers Part I: Transfer-of-technology and farming systems research. *Agricultural Administration and Extension,* 27**,** 35-52.

CHAPLAIN, V., DÉFOSSEZ, P., RICHARD, G., TESSIER, D. & ROGER-ESTRADE, J. 2011. Contrasted effects of no-till on bulk density of soil and mechanical resistance. *Soil and Tillage Research,* 111**,** 105-114.

CHEN, Y. 2019. Withdrawal of European Soil Framework Directive: Reasons and Recommendations. *Journal of Sustainable Development,* 13.

CHI, J., WALDO, S., PRESSLEY, S., O'KEEFFE, P., HUGGINS, D., STÖCKLE, C., PAN, W. L., BROOKS, E. & LAMB, B. 2016. Assessing carbon and water dynamics of no-till and conventional tillage cropping systems in the inland Pacific Northwest US using the eddy covariance method. *Agricultural and Forest Meteorology,* 218-219**,** 37-49.

CHIRINDA, N., OLESEN, J. E., PORTER, J. R. & SCHJØNNING, P. 2010. Soil properties, crop production and greenhouse gas emissions from organic and inorganic fertilizer-based arable cropping systems. *Agriculture, Ecosystems & Environment,* 139**,** 584-594.

CHOWDHURY, A. & ODAME, H. H. 2014. Social media for enhancing innovation in agri-food and rural development: current dynamics in Ontario, Canada. *Journal of rural and community development*, 8.

CLIMATE-DATA 2019. https://en.climate-data.org/europe/united-kingdom/england/bredon-61235/.

COCK, J., OBERTHÜR, T., ISAACS, C., LÄDERACH, P. R., PALMA, A., CARBONELL, J., VICTORIA, J., WATTS, G., AMAYA, A., COLLET, L., LEMA, G. & ANDERSON, E. 2011. Crop management based on field observations: Case studies in sugarcane and coffee. *Agricultural Systems,* 104**,** 755-769.

COHEN, L. & MANION, L. 1994. Research methods in education. *(4th ed.) London: Routledge*.

COHEN, L., MANION, L.& MORRISON, K. 2007. Research methods in education. London: Routledge.

COMMISSION, E. 2006. COMMUNICATION FROM THE COMMISSION TO THE COUNCIL, THE EUROPEAN PARLIAMENT, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS. *Thematic Strategy for Soil Protection,* COM(2006)231**,** 1-12.

COMMISSION, E. 2015. Comission staff working document. Report on the progress in implementation of the Water Framework Directive Programmes of Measures. SWD(2015).

CONSTANTIN, J., MARY, B., LAURENT, F., AUBRION, G., FONTAINE, A., KERVEILLANT, P. & BEAUDOIN, N. 2010. Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. *Agriculture, Ecosystems & Environment,* 135**,** 268-278.

COOK, S., COCK, J., OBERTHÜR, T. & FISHER, M. 2013. On-farm experimentation. *Better Crops,* 97**,** 17-20.

COOPER, R. J., HAMA-AZIZ, Z., HISCOCK, K. M., LOVETT, A. A., DUGDALE, S. J., SÜNNENBERG, G., NOBLE, L., BEAMISH, J. & HOVESEN, P. 2017. Assessing the farm-scale impacts of cover crops and non-inversion tillage regimes on nutrient losses from an arable catchment. *Agriculture, Ecosystems & Environment,* 237**,** 181-193.

CORNELIS, W. M., KHLOSI, M., HARTMANN, R., VAN MEIRVENNE, M. & DE VOS, B. 2005. Comparison of Unimodal Analytical Expressions for the Soil-Water Retention Curve. *Soil Science Society of America Journal,* 69.

COTE, M. & NIGHTINGALE, A. J. 2011. Resilience thinking meets social theory. *Progress in Human Geography,* 36**,** 475-489.

CRESWELL, J. W. 2003. Qualitative, Quantitative. and Mixed Methods
Approaches. *Sage Publications, Inc,* Second edition.

CRITTENDEN, S. J., POOT, N., HEINEN, M., VAN BALEN, D. J. M. & PULLEMAN, M. M. 2015. Soil physical quality in contrasting tillage systems in organic and conventional farming. *Soil and Tillage Research,* 154**,** 136-144.

CROTTY, F., MCCALMAN, H., POWELL, H., BUCKINGHAM, S. & MARLEY, C. 2019. Should farmers apply fertilizer according to when their daffodils are in flower? Utilizing a “farmer-science” approach to understanding the impact of soil temperature on spring N fertilizer application in Wales. *Soil Use and Management,* 35**,** 169-176.

CROTTY, F. V., FYCHAN, R., SANDERSON, R., RHYMES, J. R., BOURDIN, F., SCULLION, J. & MARLEY, C. L. 2016. Understanding the legacy effect of previous forage crop and tillage management on soil biology, after conversion to an arable crop rotation. *Soil Biology and Biochemistry,* 103**,** 241-252.

CULLEN, B., AMOS, D. & PADEL, S. 2016. *Organic Knowledge Network Arable OK-Net Arable-D2. 1 Description of farmer innovation groups*.

CURRY, N. & KIRWAN, J. 2014. The Role of Tacit Knowledge in Developing Networks for Sustainable Agriculture. *Sociologia Ruralis,* 54**,** 341-361.

CUTTLE, S. P., NEWELL-PRICE, J. P., HARRIS, D., CHADWICK, D. R., SHEPHERD, M. A., ANTHONY, S. G. A., MACLEOD, C. J. A., HAYGARTH, P. M. & CHAMBERS, B. J. 2016. A method-centric 'User Manual' for the mitigation of diffuse water pollution from agriculture. *Soil Use and Management,* 32**,** 162-171.

CVITANOVIC, C., MCDONALD, J. & HOBDAY, A. J. 2016. From science to action: Principles for undertaking environmentalresearch that enables knowledge exchange and evidence-baseddecision-making. *Journal of Environmental Management,* 183**,** 864-874.

CZACHOR, H. & LIPIEC, J. 2004. Quantification of soil macroporosity with image analysis. *International Agrophysics,* 18**,** 217-223.

DANIEL, T. C., SHARPLEY, A. N., EDWARDS, D. R., WEDEPOHL, R. & LEMUNYON, J. L. 1994. Minimizing surface water eutrophication from agriculture by phosphorous management. *Journal of Soil and Water Conservation,* 49**,** 30-38.

DAVIES, D. B. & FINNEY, J. B. 2002. Reduced cultivations for cereals: research, development and advisory needs under changing economic circumstances. *Research Review,* 48.

DE BAETS, S., POESEN, J., MEERSMANS, J. & SERLET, L. 2011. Cover crops and their erosion-reducing effects during concentrated flow erosion. *Catena,* 85**,** 237-244.

DE KRAKER, J. 2017. Social learning for resilience in social–ecological systems. *Current Opinion in Environmental Sustainability,* 28**,** 100-107.

DE LANGE, D., AGNEESSENS, F. & WAEGE, H. 2004. Asking Social Network Questions: A Quality Assessment of Different Measures. *Metodološki zvezki,* 1**,** 351-378.

DEASY, C., QUINTON, J. N., SILGRAM, M., BAILEY, A. P., JACKSON, B. & STEVENS, C. J. 2009. Mitigation options for sediment and phosphorus loss from winter-sown Arable Crops. *J Environ Qual,* 38**,** 2121-30.

DEFRA 2009a. Protecting our Water, Soil and Air. A Code of Good Agricultural Practice for farmers, growers and land managers.

DEFRA 2009b. Safeguarding our Soils. A Strategy for England. The Department for Environment, Food and Rural Affairs.

DEFRA 2010. Farm practices Survey 2010 - England.

DEFRA 2018. 25 Year Environmental Plan. 'A Green Future: Our 25 Year Plan to Improve the Environment', sets out what we will do to improve the environment, within a generation. Retrieved from https://www.gov.uk/government/publications/25-year-environment-plan.

DEHNEN-SCHMUTZ, K., FOSTER, G. L., OWEN, L. & PERSELLO, S. 2016. Exploring the role of smartphone technology for citizen science in agriculture. *Agronomy for Sustainable Development,* 36**,** 25.

DODDS, W. & SMITH, V. 2016. Nitrogen, phosphorus, and eutrophication in streams. *Inland Waters,* 6**,** 155-164.

DOLINSKA, A. & D'AQUINO, P. 2016. Farmers as agents in innovation systems. Empowering farmers for innovation through communities of practice. *Agricultural Systems,* 142**,** 122-130.

DOLINSKA, M. 2011. The Role of Knowledge Management and Learning of Companies in Innovation Processes. *Creativity Support Systems*.

DOMINATI, E., PATTERSON, M. & MACKAY, A. 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. *Ecological Economics,* 69**,** 1858-1868.

DONALD, P. F. & EVANS, A. D. 2006. Habitat connectivity and matrix restoration: the wider implications of agri-environment schemes. *Journal of Applied Ecology,* 43**,** 209-218.

DORAN, J. W. & ZEISS, M. R. 2000. Soil health and sustainability: managing the biotic component of soil quality. *Applied Soil Ecology,* 15**,** 3-11.

DRINKWATER, L. E. 2002. Cropping Systems Researh: Reconsidering Agricultural Experimental Approaches. *HortTechnology*, 12 (3), 355-361.

DROBNIK, T., GREINER, L., KELLER, A. & GRÊT-REGAMEY, A. 2018. Soil quality indicators – From soil functions to ecosystem services. *Ecological Indicators,* 94**,** 151-169.

DWYER, J., BERRIET-SOLLIEC, M., LATASTE, F. G., SHORT, C., MARÉCHAL, A. & HART, K. 2018. A Social-Ecological Systems Approach to Enhance Sustainable Farming and Forestry in the EU. *EuroChoices,* 17**,** 4-10.

DÖRING, T. F., BRANDT, M., HEß, J., FINCKH, M. R. & SAUCKE, H. 2005. Effects of straw mulch on soil nitrate dynamics, weeds, yield and soil erosion in organically grown potatoes. *Field Crops Research,* 94**,** 238-249.

EASTWOOD, C. R., CHAPMAN, D. F. & PAINE, M. S. 2012. Networks of practice for co-construction of agricultural decision support systems: Case studies of precision dairy farms in Australia. *Agricultural Systems,* 108**,** 10-18.

EHLERS, W. 1975. Observations of earthworm channels and infiltration on tilled and untilled loess soil. *Soil Science,* 119**,** 242-249.

ELMHOLT, S., SCHJØNNING, P., MUNKHOLM, L. J. & DEBOSZ, K. 2008. Soil management effects on aggregate stability and biological binding. *Geoderma,* 144**,** 455-467.

ENGEL, P. G. H. 1995. Facilitating Innovation : an Action-oriented Approach and Participatory Methodology to Improve Innovative Social Practice in Agriculture. *Wageningen University, Wageningen.*

ENVIRONMENT AGENCY 2008. Best farming practices.

ENVIRONMENT AGENCY 2018. Working with Natural Processes - Evidence Directory.

EUROPEAN COMMISSION 2012. The implementation of the Soil Thematic Strategy and ongoing activities. *REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS,* COM(2012) 46 final.

EUROPEAN ENVIRONMENT AGENCY 2018. European waters - assessment of status and pressures 2018. *EEA Report,* 7/2018.

FAO 2020. FAO Soils Portal. *http://www.fao.org/soils-portal/soil-degradation-restoration/en/)*.

FAO & ITPS 2015a. Status of the World's Soil Resources (SWSR) – Main Report. Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy.

FAO & ITPS 2015b. Status of the World's Soil Resources (SWSR) – Technical Summary. *Food and Agriculture Organization of the United Nations and Intergovernmental Technical Panel on Soils, Rome, Italy*.

FERNÁNDEZ-ROMERO, M. L., PARRAS-ALCÁNTARA, L., LOZANO-GARCÍA, B., CLARK, J. M. & COLLINS, C. D. 2016. Soil quality assessment based on carbon stratification index in different olive grove management practices in Mediterranean areas. *Catena,* 137**,** 449-458.

FIENER, P. & AUERSWALD, K. 2014. Rotation Effects of Potato, Maize and Winter Wheat on Water Erosion from Cultivated Land. *Advances in GeoEcology,* 38**,** 273-280.

FRANK, S., FÜRST, C., WITT, A., KOSCHKE, L. & MAKESCHIN, F. 2014. Making use of the ecosystem services concept in regional planning—trade-offs from reducing water erosion. *Landscape Ecology,* 29**,** 1377-1391.

FRANZLUEBBERS, A. J., HONS, F. M. & ZUBERER, D. A. 1995. Tillage-induced seasonal changes in soil physical properties affecting soil CO2 evolution under intensive cropping. *Soil and Tillage Research,* 34**,** 41-60.

FRØSETH, R. B., BAKKEN, A. K., BLEKEN, M. A., RILEY, H., POMMERESCHE, R., THORUP-KRISTENSEN, K. & HANSEN, S. 2014. Effects of green manure herbage management and its digestate from biogas production on barley yield, N recovery, soil structure and earthworm populations. *European Journal of Agronomy,* 52**,** 90-102.

GAINES, T. P. & GAINES, S. T. 1994. Soil texture effect on nitrate leaching in soil percolates. *Communications in Soil Science and Plant Analysis,* 25**,** 2561-2570.

GAISER, T., STAHR, K., BILLEN, N. & MOHAMMAD, M. A.-R. 2008. Modeling carbon sequestration under zero tillage at the regional scale. I. The effect of soil erosion. *Ecological Modelling,* 218**,** 110-120.

GALLOWAY, J. N., ABER, J. D., ERISMAN, J. W., SEITZINGER, S. P., HOWART, R. W., COWLING, E. B. & COSBY, B. J. 2003. The Nitrogen Cascade. *Bioscience,* 53**,** 341-356.

GALLOWAY, J. N., TOWNSEND, A. R., ERISMAN, J. W., BEKUNDA, M., CAI, Z., FRENEY, J. R., MARTINELLI, L. A., SEITZINGER, S. P. & SUTTON, M. A. 2008. Transformation of the nitrogen cycle: recent trends, questions, and potential solutions. *Science,* 320**,** 889-92.

GARBOUT, A., MUNKHOLM, L. J. & HANSEN, S. B. 2013. Tillage effects on topsoil structural quality assessed using X-ray CT, soil cores and visual soil evaluation. *Soil and Tillage Research,* 128**,** 104-109.

GARDI, C., JEFFERY, S. & SALTELLI, A. 2013. An estimate of potential threats levels to soil biodiversity in EU. *Global Change Biology,* 19**,** 1538-1548.

GARFORTH, C., ANGELL, B., ARCHER, J. & GREEN, K. 2002. Improving access to advice for land managers:
a literature review of recent developments in extension and advisory services. *DEFRA Research Project KT0110*, 1-23.

GIDDENS, A. 1984. The Constitution of Society: Outline of the Theory of Structuration. *Polity Press, Cambridge*.

GISSI, E., GAGLIO, M., ASCHONITIS, V. G., FANO, E. A. & REHO, M. 2018. Soil-related ecosystem services trade-off analysis for sustainable biodiesel production. *Biomass and Bioenergy,* 114**,** 83-99.

GLÆSNER, N., HELMING, K. & DE VRIES, W. 2014. Do Current European Policies Prevent Soil Threats and Support Soil Functions? *Sustainability,* 6**,** 9538-9563.

GOLABI, M. H., RADCLIFFE, D. E., HARGROVE, W. L. & TOLLNER, E. W. 1995. Macropore effects in conventional tillage and no-tillage soils. *Journal of Soil and Water Conservation,* 50**,** 205-210.

GORARD, G. 2004. Combining methods in educational and social research. *Berkshire: Open University Press*.

GOTZE, P., RUCKNAGEL, J., JACOBS, A., MARLANDER, B., KOCH, H. J. & CHRISTEN, O. 2016. Environmental impacts of different crop rotations in terms of soil compaction. *J Environ Manage,* 181**,** 54-63.

GOUGOULIAS, C., CLARK, J. M. & SHAW, L. J. 2014. The role of soil microbes in the global carbon cycle: tracking the below-ground microbial processing of plant-derived carbon for manipulating carbon dynamics in agricultural systems. *J Sci Food Agric,* 94**,** 2362-71.

GRAJALES III, F. J., SHEPS, S., HO, K., NOVAK-LAUSCHER, H. & EYSENBACH, G. 2014. Social media: a review and tutorial of applications in medicine and health care. *Journal of medical Internet research,* 16.

GRANOVETTER, M. 1983. THE STRENGTH OF WEAK TIES: A NETWORK THEORY REVISITED. *Sociological Theory,* 1**,** 201-233.

GRAVES, A. R., MORRIS, J., DEEKS, L. K., RICKSON, R. J., KIBBLEWHITE, M. G., HARRIS, J. A., FAREWELL, T. S. & TRUCKLE, I. 2015. The total costs of soil degradation in England and Wales. *Ecological Economics,* 119**,** 399-413.

GRAY, B. J. & GIBSON, J. W. 2013. Actor-Networks, Farmer Decisions, and Identity. *Culture, Agriculture, Food and Environment,* 35**,** 82-101.

GREEN, T. R., AHUJA, L. R. & BENJAMIN, J. G. 2003. Advances and challenges in predicting agricultural management effects on soil hydraulic properties. *Geoderma,* 116**,** 3-27.

GREINER, L., KELLER, A., GRÊT-REGAMEY, A. & PAPRITZ, A. 2017. Soil function assessment: review of methods for quantifying the contributions of soils to ecosystem services. *Land Use Policy,* 69**,** 224-237.

GUBA, E.G. & LINCOLN, Y. S. 1994. Competing paradigms in qualitative research. In Denzin N.K. and Lincoln Y.S. (Eds), Handbook of qualitative research. *Thousand Oaks, CA: Sage*, 105-117.

GÓMEZ-LIMÓN, J. A., ARRIAZA, M. & BERBEL, J. 2002. Conflicting implementation of agricultural and water policies in irrigated areas in the EU. *Journal of Agricultural Economics,* 53**,** 259-282.

HALL, A. 2005. The linear model of innovation: the historical construction of an analytical framework science. *Technology & Human Values,* 31**,** 639-667.

HALL, A., RASHEED SULAIMAN, V., CLARK, N. & YOGANAND, B. 2003. From measuring impact to learning institutional lessons: an innovation systems perspective on improving the management of international agricultural research. *Agricultural Systems,* 78**,** 213-241.

HALL, A. J., YOGANAND, B., SULAIMAN, R. V., RAJESWARI RAINA, S., SHAMBU PRASAD, C., NAIK GURU, C. & CLARK, N. G. 2004. Innovations in innovation: reflections on partnership, institutions and learning. *ICRISAT, Andra Pradesh*.

HANGEN, E., BUCZKO, U., BENS, O., BRUNOTTE, J. & HÜTTL, R. F. 2002. Infiltration patterns into two soils under conventional and conservation tillage: influence of the spatial distribution ofplant root structures and soil animal activity. *Soil and Tillage Research,* 63**,** 181-186.

HANSEN, B., KRISTENSEN, E. S., GRANT, R., HØGH-JENSEN, H., SIMMELSGARD, S. E. & OLESEN, J. E. 2000. Nitrogen leaching from conventional versus organic farming systems — a systems modelling approach. *European Journal of Agronomy,* 13**,** 65-82.

HANSEN, E. M., MUNKHOLM, L. J., OLESEN, J. E. & MELANDER, B. 2015. Nitrate leaching, yields and carbon sequestration after noninversion tillage, catch crops, and straw retention. *J Environ Qual,* 44**,** 868-81.

HASSAN, R., SCHOLES, R. J. & ASH, N. 2005. Ecosystems and Human Well-Being: Current State and Trends: Findings of the Condition and Trends Working Group

(Millennium Ecosystem Assessment Series). *Ecosystems and Human Well-being, Ecosystems and Human Well-being, Island Press,* 1.

HAYGARTH, P. M. & RITZ, K. 2009. The future of soils and land use in the UK: Soil systems for the provision ofland-based ecosystem services. *Land Use Policy,* 26**,** 187–197.

HAYTHORNTHWAITE, C. 1996. Social network analysis: An approach and technique for the study of information exchange. *Library & Information Science Research,* 18**,** 323-342.

HAZARIKA, S., PARKINSON, R., BOL, R., DIXON, L., RUSSELL, P., DONOVAN, S. & ALLEN, D. 2009. Effect of tillage system and straw management on organic matter dynamics. *Agronomy for Sustainable Development,* 29**,** 525-533.

HILTON, J., O'HARE, M., BOWES, M. J. & JONES, J. I. 2006. How green is my river? A new paradigm of eutrophication in rivers. *Sci Total Environ,* 365**,** 66-83.

HIMANSHU, S. K., PANDEY, A., YADAV, B. & GUPTA, A. 2019. Evaluation of best management practices for sediment and nutrient loss control using SWAT model. *Soil & Tillage Research,* 192, 42-58.

HISLOP, D. 2002. Mission impossible? Communicating and sharing knowledge via information technology. *Journal of Information Technology,* 17**,** 165-177.

HOBBS, P. R., SAYRE, K. & GUPTA, R. 2008. The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 363**,** 543.

HONISCH, M., HELLMEIER, C. & WEISS, K. 2002. Response of surface and subsurface water quality to land use changes. *Geoderma,* 105**,** 277-298.

HOREL, Á., TÓTH, E., GELYBÓ, G., KÁSA, I., BAKACSI, Z. & FARKAS, C. 2015. Effects of Land Use and Management on Soil Hydraulic Properties. *Open Geosciences,* 7.

HOUSE OF COMMONS 2016. Environmental Audit Committee on Soil Health. *First repport of 2016-2017*.

HUBERT, F., HALLAIRE, V., SARDINI, P., CANER, L. & HEDDADJ, D. 2007. Pore morphology changes under tillage and no-tillage practices. *Geoderma,* 142**,** 226-236.

HUGGINS, D. R. & REGANOLD, J. P. 2008. No-Till: the Quiet Revolution. *Scientific American, a division of Nature America,* 299**,** 70-77.

HÖSL, R. & STRAUSS, P. 2016. Conservation tillage practices in the alpine forelands of Austria — Are they effective? *Catena,* 137**,** 44-51.

INGRAM, J. 2008. Are farmers in England equipped to meet the knowledge challenge of sustainable soil management? An analysis of farmer and advisor views. *J Environ Manage,* 86**,** 214-28.

INGRAM, J. 2010. Technical and Social Dimensions of Farmer Learning: An Analysis of the Emergence of Reduced Tillage Systems in England. *Journal of Sustainable Agriculture,* 34**,** 183-201.

INGRAM, J. 2015. Framing niche-regime linkage as adaptation: An analysis of learningand innovation networks for sustainable agriculture across Europe. *Journal of Rural Studies,* 40**,** 59-75.

INGRAM, J., MAYE, D., KIRWAN, J., CURRY, N. & KUBINAKOVA, K. 2014. Learning in the Permaculture Community of Practice in England: An Analysis of the Relationship between Core Practices and Boundary Processes. *The Journal of Agricultural Education and Extension,* 20**,** 275-290.

INGRAM, J. & MILLS, J. 2019a. Are advisory services "fit for purpose" to support sustainable soil management? An assessment of advice in Europe. *Soil Use and Management,* 35**,** 21-31.

INGRAM, J. & MILLS, J. 2019b. Are advisory services "fit for purpose" to support sustainable soil management? An assessment of advice in Europe.

ISAAC, M. E. 2012. Agricultural information exchange and organizational ties: The effect of network topology on managing agrodiversity. *Agricultural Systems,* 109**,** 9-15.

ISAAC, M. E., ERICKSON, B. H., QUASHIE-SAM, S. J. & TIMMER, V. R. 2007. Transfer of Knowledge on Agroforestry Management Practices: the Structure of Farmer Advice Networks. *Ecology and Society,* 12**,** 32.

IUSS 2006. World Reference Base for Soil Resources. *FAO,* Rome.

JARVIS, N., FORKMAN, J., KOESTEL, J., KÄTTERER, T., LARSBO, M. & TAYLOR, A. 2017. Long-term effects of grass-clover leys on the structure of a silt loam soil in a cold climate. *Agriculture, Ecosystems & Environment,* 247**,** 319-328.

JASIMUDDIN, S. M., CHAHARBAGHI, K., KLEIN, J. H. & CONNELL, C. 2005. The paradox of using tacit and explicit knowledge. *Management Decision,* 43**,** 102-112.

JEFFERY, S., GARDI, C., JONES, A., MONTANARELLA, L., MARMO, L., MIKO, L., RITZ, K., PERES, G., RÖMBKE, J. & VAN DER PUTTEN, W. H. 2010. European Atlas of Soil Biodiversity. *Office for Official Publications of the European Communities: Luxembourg***,** 128.

JONES, A., PANAGOS, P., BARCELO, S., BOURAOUI, F., BOSCO, C., DEWITTE, O., GARDI, C., ERHARD, M., HERVAS DE DIEGO, F., HIEDERER, R., JEFFERY, S. & AL., E. 2010. The State of Soil in Europe—A Contribution of the JRC to the European Environment Agency's Environment State and Outlook Report—SOER. *Office for Official Publications of the European Communities: Luxembourg*, 76.

JONES, A., PANAGOS, P., BARCELO, S., BOURAOUI, F., BOSCO, C., DEWITTE, O., GARDI, C., ERHARD, M., HERVÁS, J., HIEDERER, R. & JEFFERY, S. 2012. The state of soil in Europe (SOER). JRC reference reports. Report, 25186.

JONES, J. I., MURPHY, J. F., ANTHONY, S. G., ARNOLD, A., BLACKBURN, J. H., DUERDOTH, C. P., HAWCZAK, A., HUGHES, G. O., PRETTY, J. L., SCARLETT, P. M., GOODAY, R. D., ZHANG, Y. S., FAWCETT, L. E., SIMPSON, D., TURNER, A. W. B., NADEN, P. S., SKATES, J. & MCKENZIE, A. 2017. Do agri-environment schemes result in improved water quality? *Journal of Applied Ecology,* 54**,** 537-546.

KAINIEMI, V., ARVIDSSON, J. & KÄTTERER, T. 2015. Effects of autumn tillage and residue management on soil respiration in a long-term field experiment in Sweden. *Journal of Plant Nutrition and Soil Science,* 178**,** 189-198.

KALLIO, H., PIETILÄ, A.-M., JOHNSON, M. & KANGASNIEMI, M. 2016. Systematic methodological review: developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing,* 72**,** 2954-2965.

KASSAM, A., DERPSCH, R. & FRIEDRICH, T. 2014. Global achievements in soil and water conservation: The case of Conservation Agriculture. *International Soil and Water Conservation Research,* 2**,** 5-13.

KASSAM, A., FRIEDRICH, T., DERPSCH, R. & KIENZLE, J. 2015. Overview of the Worldwide Spread of Conservation Agriculture. *The Journal of Field Actions,* 8.

KASSAM, A., FRIEDRICH, T., DERPSCH, R., LAHMAR, R., MRABET, R., BASCH, G., GONZÁLEZ-SÁNCHEZ, E. J. & SERRAJ, R. 2012. Conservation agriculture in the dry Mediterranean climate. *Field Crops Research,* 132**,** 7-17.

KAUTZ, T., LÜSEBRINK, M., PÄTZOLD, S., VETTERLEIN, D., PUDE, R., ATHMANN, M., KÜPPER, P. M., PERKONS, U. & KÖPKE, U. 2014. Contribution of anecic earthworms to biopore formation during cultivation of perennial ley crops. *Pedobiologia,* 57**,** 47-52.

KECHAVARZI, C., ŠPONGROVÁ, K., DRESSER, M., MATULA, S. & GODWIN, R. J. 2009. Laboratory and field testing of an automated tension infiltrometer. *Biosystems Engineering,* 104**,** 266-277.

KEISELMEIER, J., CHANDRASEKHAR, P., WENINGER, T., ACHWEN, A., JULICH, S., FEGER, K. & SCHWÄRZEL, K. 2019. Quantification of soil pore dynamics during a winter wheat cropping cycle under different tillage practices. *Soil and Tillage Research,* 192, 222-232.

KIBBLEWHITE, M. G., JONES, R. J. A., MONTANARELLA, L., BARITZ, R., HUBER, S., ARROUAYS, D., MICHELI, E. & STEPHENS, M. 2008. Environmental Assessment of Soil for Monitoring Volume VI: Soil Monitoring System for Europe. *JRC Scientific and Technical Reports,* EUR 23490.

KILELU, C. W., KLERKX, L., LEEUWIS, C. & HALL, A. 2011. Beyond knowledge brokerage: An exploratory study of innovation intermediaries in an evolving smallholder agricultural system in Kenya. *UNU-MERIT Working Papers,* 2011-022**,** 1-39.

KILPATRICK, S. & FALK, I. 1999. Benefits for all: how learning for farming can build social capital in communities. *Launceston, Tasmania: University of Tasmania*.

KISTNER, I., OLLESCH, G., MEISSNER, R. & RODE, M. 2013. Spatial-temporal dynamics of water soluble phosphorus in the topsoil of a low mountain range catchment. *Agriculture, Ecosystems & Environment,* 176**,** 24-38.

KLERKX, L., AARTS, N. & LEEUWIS, C. 2010. Adaptive management in agricultural innovation systems: The interactions between innovation networks and their environment. *Agricultural Systems,* 103**,** 390-400.

KLERKX, L. & LEEUWIS, C. 2008. Matching demand and supply in the agricultural knowledge infrastructure: Experiences with innovation intermediaries. *Food Policy,* 33**,** 260-276.

KLERKX, L. & PROCTOR, A. 2013. Beyond fragmentation and disconnect: Networks for knowledge exchange in the English land management advisory system. *Land Use Policy,* 30**,** 13-24.

KLERKX, L., SCHUT, M., LEEVWIS, C. & KILELU, C. 2012. Advances in Knowledge Brokering in the Agricultural Sector: Towards Innovation System Facilitation. *IDS Bulletin,* 43.

KNAPEN, A., POESEN, J. & BAETS, S. D. 2008a. Rainfall-induced consolidation and sealing effects on soil erodibility during concentrated runoff for loess-derived topsoils. *Earth Surface Processes and Landforms,* 33**,** 444-458.

KNAPEN, A., POESEN, J. & DEBAETS, S. 2007. Seasonal variations in soil erosion resistance during concentrated flow for a loess-derived soil under two contrasting tillage practices. *Soil and Tillage Research,* 94**,** 425-440.

KNAPEN, A., POESEN, J., GOVERS, G. & DE BAETS, S. 2008b. The effect of conservation tillage on runoff erosivity and soil erodibility during concentrated flow. *Hydrological Processes,* 22**,** 1497-1508.

KNOWLER, D. & BRADSHAW, B. 2007. Farmers' adoption of conservation agriculture: A review and synthesis of recent research. *Food Policy,* 32**,** 25-48.

KOSCHKE, L., FÜRST, C., LORENZ, M., WITT, A., FRANK, S. & MAKESCHIN, F. 2013. The integration of crop rotation and tillage practices in the assessment of ecosystem services provision at the regional scale. *Ecological Indicators,* 32**,** 157-171.

KRZYWOSZYNSKA, A. 2018. Making knowledge and meaning in communities of practice: What role may science play? The case of sustainable soil management in England. *Soil Use and Management,* 35**,** 160-168.

LAFORGE, J. M. L. & MCLACHLAN, S. M. 2018. Learning communities and new farmer knowledge in Canada. *Geoforum,* 96**,** 256-267.

LAHMAR, R. 2010a. Adoption of conservation agriculture in Europe. *Land Use Policy,* 27**,** 4-10.

LAHMAR, R. 2010b. Adoption of conservation agriculture in Europe: lessons of the KASSA project. *Land use policy,* 27**,** 4-10.

LAL, R. 2015. Restoring Soil Quality to Mitigate Soil Degradation. *Sustainability,* 7**,** 5875-5895.

LAL, R. & STEWART, B. A. 2012. *Soil Degradation: A Global Threat,* Springer Science & Business Media, Springer-Verlag.

LAMBIN, E. F. & MEYFROIDT, P. 2010. Land use transitions: Socio-ecological feedback versus socio-economic change. *Land Use Policy,* 27**,** 108-118.

LANDMARK, 2018. http://landmark2020.eu/

LANDWISE, 2020. https://landwise-nfm.org/

LANKESTER, A. J. 2013. Conceptual and operational understanding of learning for sustainability: a case study of the beef industry in north-eastern Australia. *J Environ Manage,* 119**,** 182-93.

LEEUWIS, C. & VAN DEN BAN, A. 2004. Communication for Rural Innovation: Rethinking Agricultural Extension. *Oxford : Blackwell Science*.

LEHÉBEL-PÉRON, A., SIDAWY, P., DOUNIAS, E. & SCHATZ, B. 2016. Attuning local and scientific knowledge in the context of global change: The case of heather honey production in southern France. *Journal of Rural Studies,* 44**,** 132-142.

LEYS, A., GOVERS, G., GILLIJNS, K. & POESEN, J. 2007. Conservation tillage on loamy soils: explaining the variability in interrill runoff and erosion reduction. *European Journal of Soil Science,* 58**,** 1425-1436.

LI, F.-Y., LIANG, X.-Q., LIU, Z.-W. & TIAN, G.-M. 2019. No-till with straw return retains soil total P while reducing loss potential of soil colloidal P in rice-fallow systems. *Agriculture, Ecosystems & Environment,* 286.

LINDBORG, R., GORDON, L. J., MALINGA, R., BENGTSSON, J., PETERSON, G., BOMMARCO, R., DEUTSCH, L., GREN, Å., RUNDLÖF, M. & SMITH, H. G. 2017. How spatial scale shapes the generation and management of multiple ecosystem services. *Ecosphere,* 8**,** 1-15.

LIPIEC, J. & HATANO, R. 2003. Quantification of compaction effects on soil physical properties and crop growth. *Geoderma,* 116**,** 107-136.

LIPIEC, J., KUŚ, J., SŁOWIŃSKA-JURKIEWICZ, A. & NOSALEWICZ, A. 2006. Soil porosity and water infiltration as influenced by tillage methods. *Soil and Tillage Research,* 89**,** 210-220.

LIU, Q., YASUFUKU, N., OMINE, K. & HAZARIKA, H. 2012. Automatic soil water retention test system with volume change measurement for sandy and silty soils. *Soils and Foundations,* 52**,** 368-380.

LIU, T., BRUINS, R. J. F. & HEBERLING, M. T. 2018. Factors Influencing Farmers' Adoption of Best Management Practices: A Review and Synthesis. *Sustainability,* 10**,** 432.

LOGSDON, S. D. 2012. Temporal Variability of Bulk Density and Soil Water at Selected Field Sites. *Soil Science,* 177**,** 327-331.

LUBELL, M., NILES, M. & HOFFMAN, M. 2014. Extension 3.0: Managing Agricultural Knowledge Systems in the Network Age. *Society & Natural Resources,* 27**,** 1089-1103.

LUNDEKVAM, H. E. 2007. Plot studies and modelling of hydrology and erosion in southeast Norway. *Catena,* 71**,** 200-209.

LYON, A., BELL, M. M., GRATTON, C. & JACKSON, R. 2011. Farming without a recipe: Wisconsin graziers and new directions for agricultural science. *Journal of Rural Studies,* 27**,** 384-393.

MACKENZIE, N. & KNIPE, S. 2006. Research dilemmas: Paradigms, methods and methodology. *Issues In Educational Research,* 16.

MADDISON, D. 2007. The perception of and adaptation to climate change in africa. *World Bank Policy Research Working Paper 4308 (Washington DC, USA: World Bank)*.

MAILLARD, E., MCCONKEY, B. G. & ANGERS, D. A. 2017. Increased uncertainty in soil carbon stock measurement with spatial scale and samplin profile depth in world grasslands: A systematic analysis. *Agriculture, Ecosystems and Environment.* 236, 268-276.

MANN, S. 2018. Conservation by Innovation: What Are the Triggers for Participation Among Swiss Farmers? *Ecological Economics,* 146**,** 10-16.

MARSDEN, P. V. 1990. Network data and measurement. *Annu. Rev. Soc.,* 16**,** 435-463.

MARTIN, G. 2015. A conceptual framework to support adaptation of farming systems–development and application with Forage Rummy. *Agricultural Systems,* 132**,** 52-61.

MARTIN, P., JOANNON, A. & PISKIEWICZ, N. 2010. Temporal variability of surface runoff due to cropping systems in cultivated catchment areas: Use of the DIAR model for the assessment of environmental public policies in the Pays de Caux (France). *J Environ Manage,* 91**,** 869-78.

MARTÍNEZ, I., CHERVET, A., WEISSKOPF, P., STURNY, W. G., ETANA, A., STETTLER, M., FORKMAN, J. & KELLER, T. 2016. Two decades of no-till in the Oberacker long-term field experiment: Part I. Crop yield, soil organic carbon and nutrient distribution in the soil profile. *Soil and Tillage Research,* 163**,** 141-151.

MATERIA, V. C., GIARÈ, F. & KLERKX, L. 2015. Increasing Knowledge Flows between the Agricultural Research and Advisory System in Italy: Combining Virtual and Non-virtual Interaction in Communities of Practice. *The Journal of Agricultural Education and Extension,* 21**,** 203-218.

MCGINNIS, M. D. & OSTROM, E. 2014. Social-ecological system framework: initial changes and continuing

challenges. *Ecology and Society,* 19**,** 30.

MCGONIGLE, D. F., HARRIS, R. C., MCCAMPHILL, C., KIRK, S., DILS, J., MACDONALD, S. & BAILEY, S. 2012. Towards a more strategic approach to research to support catchment-based policy approaches to mitigate agricultural water pollution: a UK case-study. *Environmental Science & Policy,* 24**,** 4-14.

MCPHERSON, M., SMITH-LOVIN, L. & COOK, J. M. 2001. Birds of a Feather: Homophily in Social Networks. *Annu. Rev. Sociol.,* 27**,** 415-44.

MEHRING, P., GEOGHEGAN, H., CLOKE, H. L. & CLARK, J. M. 2018. What is going wrong with community engagement? How flood communities and flood authorities construct engagement and partnership working. *Environmental Science & Policy,* 89**,** 109-115.

MEYER, M. 2010. The Rise of the Knowledge Broker. *Science Communication,* 32**,** 118-127.

MEYSMAN, F. J., MIDDELBURG, J. J. & HEIP, C. H. 2006. Bioturbation: a fresh look at Darwin's last idea. *Trends Ecol Evol,* 21**,** 688-95.

MHAZO, N., CHIVENGE, P. & CHAPLOT, V. 2016. Tillage impact on soil erosion by water: Discrepancies due to climate and soil characteristics. *Agriculture, Ecosystems & Environment,* 230**,** 231-241.

MILESTAD, R., KUMMER, S. & VOGL, C. R. 2010a. Building farm resilience through farmers' experimentation. *9th European IFSA Symposium***,** 770-778.

MILESTAD, R., WESTBERG, L., GEBER, U. & BJÖRKLUND, J. 2010b. Enhancing Adaptive Capacity in Food Systems: Learning at Farmers' Markets in Sweden. *Ecology and Society,* 15**,** 29.

MILLENIUM ECOSYSTEM ASSESSMENT (PROGRAM) 2005. Ecosystems and human well-being. *Washington, D. C., Island Press*.

MILLER, T. R., BAIRD, T. D., LITTLEFIELD, C. M., KOFINAS, G. & CHAPIN III, F. S. 2008. Epistemological Pluralism: Reorganizing Interdisciplinary Research. *Ecology and Society,* 13**,** 46.

MILLS, J., GASKELL, P., INGRAM, J., DWYER, J., REED, M. & SHORT, C. 2016. Engaging farmers in environmental management through a better understanding of behaviour. *Agriculture and Human Values,* 34**,** 283-299.

MILLS, J., REED, M., SKAALSVEEN, K., INGRAM, J. & BRUYN, L. L. 2019. The use of Twitter for knowledge exchange on sustainable soil management. *Soil Use and Management,* 35**,** 195-203.

MILONE, P. & VENTURA, F. 2019. New generation farmers: Rediscovering the peasantry. *Journal of Rural Studies,* 65**,** 43-52.

MOAYEDI, A. A. & AZIZI, M. 2012. Improvement of Knowledge and Skills Level of Wheat-Cultivating Farmers using On-Farm Researches. *Procedia - Social and Behavioral Sciences,* 46**,** 2258-2261.

MONCADA, M. P., PENNING, L. H., TIMM, L. C., GABRIELS, D. & CORNELIS, W. M. 2014. Visual examinations and soil physical and hydraulic properties for assessing soil structural quality of soils with contrasting textures and land uses. *Soil and Tillage Research,* 140**,** 20-28.

MONTANARELLA, L. & VARGAS, R. 2012. Global governance of soil resources as a necessary condition for sustainable development. *Current opinion in environmental sustainability,* 4**,** 559-564.

MONTGOMERY, D. R. 2007. Soil erosion and agricultural sustainability. *Proceedings of the National Academy of Sciences,* 104**,** 13268-13272.

MORGAN, S. L. 2011. Social Learning among Organic Farmers and the Application of the Communities of Practice Framework. *The Journal of Agricultural Education and Extension,* 17**,** 99-112.

MORRIS, N. L., MILLER, P. C. H., J.H.ORSON & FROUD-WILLIAMS, R. J. 2010. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil, crops and the environment—A review. *Soil and Tillage Research,* 108**,** 1-15.

MORRIS, W. & JAMES, P. 2017. Social media, an entrepreneurial opportunity for agriculture-based enterprises. *Journal of Small Business and Enterprise Development*, 24, 1028-1045.

MUELLER, L., KAY, B. D., DEEN, B., HU, C., ZHANG, Y., WOLFF, M., EULENSTEIN, F. & SCHINDLER, U. 2009a. Visual assessment of soil structure: Part II. Implications of tillage, rotation and traffic on sites in Canada, China and Germany. *Soil and Tillage Research,* 103**,** 188-196.

MUELLER, L., KAY, B. D., HU, C., LI, Y., SCHINDLER, U., BEHRENDT, A., SHEPHERD, T. G. & BALL, B. C. 2009b. Visual assessment of soil structure: Evaluation of methodologies on sites in Canada, China and Germany. *Soil and Tillage Research,* 103**,** 178-187.

MUNKHOLM, L. J., SCHJØNNING, P., RASMUSSEN, K. J. & TANDERUP, K. 2003. Spatial and temporal effects of direct drilling on soil structure in the seedling environment. *Soil and Tillage Research,* 71**,** 163-173.

MUNSHI, K. 2004. Social learning in a heterogeneous population: technology diffusion in the Indian Green Revolution. *Journal of Development Economics,* 73**,** 185-213.

NEWBURY, E., HUMPHREYS, L. & FUESS, L. 2014. Over the Hurdles: Barriers to Social Media Use in Extension Offices. *Journal of Extension*, 52, n5.

NEWELL-PRICE, H. D., TAYLOR, M., WILLIAMS, J. R., ANTHONY, S. G., DUETHMANN, D., GOODAY, R. D., LORD, E. I., CHAMBERS, B. J., CHADWICK, D. R. & MISSELBROOK, T. H. 2011. An Inventory of Mitigation Methods and Guide to Their Effects on Diffuse Water Pollution, Greenhouse Gas Emissions and Ammonia Emissions from Agriculture. *Report prepared as part of Defra Project WQ0106*.

NONAKA, I. 1994. A dynamic theory of organizational knowledge creation. *Organization Science,* 5**,** 14-37.

NUTHALL, P. L. & OLD, K. M. 2018. Intuition, the farmers' primary decision process. A review and analysis. *Journal of Rural Studies,* 58**,** 28-38.

O'SULLIVAN, L., CREAMER, R. E., FEALY, R., LANIGAN, G., SIMO, I., FENTON, O., CARFRAE, J. & SCHULTE, R. P. O. 2015. Functional Land Management for managing soil functions: A case-study of the trade-off between primary productivity and carbon storage in response to the intervention of drainage systems in Ireland. *Land Use Policy,* 47**,** 42-54.

O'SULLIVAN, L., WALL, D., CREAMER, R., BAMPA, F. & SCHULTE, R. P. O. 2018. Functional Land Management: Bridging the Think-Do-Gap using a multi-stakeholder science policy interface. *Ambio,* 47**,** 216-230.

OENEMA, O., OUDENDAG, D. & VELTHOF, G. L. 2007. Nutrient losses from manure management in the European Union. *Livest. Sci.,* 112**,** 261-272.

OERLEMANS, N. & ASSOULINE, G. 2004. Enhancing farmers' networking strategies for sustainable development. *Journal of Cleaner Production,* 12**,** 469-478.

OKPARA, U. T., STRINGER, L. C., AKHTAR-SCHUSTER, M., METTERNICHT, G. I., DALLIMER, M. & REQUIER-DESJARDINS, M. 2018. A social-ecological systems approach is necessary to achieve land degradation neutrality. *Environmental Science & Policy,* 89**,** 59-66.

OLDEMAN, L. R. 2012. Global Extent of Soil Degradation. *ISRIC Bi-Annual Report,* 1991-1992, 19-36.

OORTS, K., LAURENT, F., MARY, B., THIEBEAU, P., LABREUCHE, J. & NICOLARDOT, B. 2007. Experimental and simulated soil mineral N dynamics for long-term tillage systems in northern France. *Soil and Tillage Research,* 94, 441-456.

OORTS, K., NICOLARDOT, B., MERCKX, R., RICHARD, G. & BOIZARD, H. 2006. C and N mineralization of undisrupted and disrupted soil from different structural zones of conventional tillage and no-tillage systems in northern France. *Soil Biology and Biochemistry,* 38, 2576-2586.

ORESZCZYN, S., LANE, A. & CARR, S. 2010. The role of networks of practice and webs of influencers on farmers' engagement with and learning about agricultural innovations. *Journal of Rural Studies,* 26, 404-417.

OSTROM, E. 2007. A diagnostic approach for going beyond panaceas. *Proc Natl Acad Sci U S A,* 104, 15181-7.

OSTROM, E. 2009. A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science, New Series,* 325, 419-422.

OUSSIBLE, M. & CROOKSTON, R. K. 1992. Subsurface Compaction Reduces the Root and Shoot Growth and Grain Yield of Wheat. *Agrionomy Journal,* 84, 34-38.

O'KANE, M. P., PAINE, M. S. & KING, B. J. 2008. Context, Participation and Discourse: The Role of the Communities of Practice Concept in Understanding Farmer Decision-Making. *The Journal of Agricultural Education and Extension,* 14.

PADEL, S. 2001. Conversion to Organic Farming: A Typical Example of the Diffusion of an Innovation? *Sociologia Ruralis,* 41.

PALEARI, S. 2017. Is the European Union protecting soil? A critical analysis of Community environmental policy and law. *Land Use Policy,* 64, 163-173.

PALMER, S. 2016 The representation of engineering education as a social media topic on Twitter. PAEE/ALE 2016: Proceedings of the 8th International Symposium on Project Approaches in Engineering Education and 14th Active Learning in Engineering Education Combined Conference and Workshop, 2016. Project Approaches in Engineering Education Association, 37-44.

PEEL, M. C., FINLAYSON, B. L. & MCMAHON, T. A. 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences,* 11, 1633-1644.

PEI, S., MUCHNIK, L., ANDRADE, J. S., JR., ZHENG, Z. & MAKSE, H. A. 2014. Searching for superspreaders of information in real-world social media. *Sci Rep,* 4**,** 5547.

PEIGNÉ, J., CANNAVACIUOLO, M., GAUTRONNEAU, Y., AVELINE, A., GITEAU, J. L. & CLUZEAU, D. 2009. Earthworm populations under different tillage systems in organic farming. *Soil and Tillage Research,* 104**,** 207-214.

PEIGNÉ, J., VIAN, J.-F., CANNAVACCIUOLO, M., LEFEVRE, V., GAUTRONNEAU, Y. & BOIZARD, H. 2013. Assessment of soil structure in the transition layer between topsoil and subsoil using the profil cultural method. *Soil and Tillage Research,* 127**,** 13-25.

PELOSI, C., GRANDEAU, G. & CAPOWIEZ, Y. 2017. Temporal dynamics of earthworm-related macroporosity in tilled and non-tilled cropping systems. *Geoderma,* 289**,** 169-177.

PERKINS, A. J., MAGGS, H. E., WATSON, A. & WILSON, J. D. 2011. Adaptive management and targeting of agri-environment schemes does benefit biodiversity: a case study of the corn bunting Emberiza calandra. *Journal of Applied Ecology,* 48**,** 514-522.

PEUKERT, S., BOL, R., ROBERTS, W., MACLEOD, C. J. A., MURRAY, P. J., DIXON, E. R. & BRAZIER, R. E. 2012. Understanding spatial variability of soil properties: a key step in establishing field- to farm-scale agro-ecosystem experiments. *Rapid Communications in Mass Spectometry,* 26.

PIEPHO, H.-P., RICHTER, C., SPILKE, J., HARTUNG, K., KUNICK, A. & THÖLE, H. 2011. Statistical aspects of on-farm experimentation. *Crop and Pasture Science,* 62.

PIRON, D., BOIZARD, H., HEDDADJ, D., PÉRÈS, G., HALLAIRE, V. & CLUZEAU, D. 2017. Indicators of earthworm bioturbation to improve visual assessment of soil structure. *Soil and Tillage Research,* 173**,** 53-63.

PONCET, J., KUPER, M. & CHICHE, J. 2010. Wandering off the paths of planned innovation: The role of formal and informal intermediaries in a large-scale irrigation scheme in Morocco. *Agricultural Systems,* 103**,** 171-179.

POSTHUMUS, H. & MORRIS, J. 2010. Implications of CAP reform for land management and runoff control in England and Wales. *Land Use Policy,* 27**,** 42-50.

POWLSON, D.S., BHOGAL, A., CHAMBERS, B. J., COLEMAN, K. & MACDONALD, A.J. The potential to increase soil carbon stocks through reduced tillage or organic material additions in England and Wales: A case study. *Agriculture, Ecosystems and Environment,* 146, 23-33.

PRAGER, K. & POSTHUMUS, H. 2010. Socio-economic factors influencing farmers' adoption of soil conservation practices in Europe. *In:* NAPIER, T. L. (ed.) *Human Dimensions of Soil and Water Conservation.* Nova Science Publishers, Inc.

PRASUHN, V. 2012. On-farm effects of tillage and crops on soil erosion measured over 10 years in Switzerland. *Soil and Tillage Research,* 120**,** 137-146.

PRIBYL, D. W. 2010. A critical review of the conventional SOC to SOM conversion factor. *Geoderma,* 156, 75-83.

PROKOPY, L. S., FLORESS, K., KLOTTHOR-WEINKAUF, D. & BAUMGART-GETZ, A. 2008. Determinants of agricultural best management practice adoption: Evidence from the literature. *Journal of Soil and Water Conservation,* 63**,** 300-311.

PULIDO MONCADA, M., HELWIG PENNING, L., TIMM, L. C., GABRIELS, D. & CORNELIS, W. M. 2014. Visual examinations and soil physical and hydraulic properties for assessing soil structural quality of soils with contrasting textures and land uses. *Soil and Tillage Research,* 140**,** 20-28.

RAMIREZ, A. 2013. The Influence of Social Networks on Agricultural Technology Adoption. *Procedia - Social and Behavioral Sciences,* 79**,** 101-116.

RANI, A., BANDYOPADHYAY, K. K., KRISHNAN, P., SARANGI, A. & DATTA, S. P. 2017. Effect of Tillage, Residue and Nitrogen Management on Soil Mineral Nitrogen Dynamics and Nitrogen Use Efficiency of Wheat Crop in an Inceptisol. *Journal of Agricultural Physics,* 17**,** 16-30.

RAY, D. K., MUELLER, N. D., WEST, P. C. & FOLEY, J. A. 2013. Yield trends are insufficient to double global crop production by 2050. *PloS one,* 8**,** e66428.

RAY, D. K., RAMANKUTTY, N., MUELLER, N. D., WEST, P. C. & FOLEY, J. A. 2012. Recent patterns of crop yield growth and stagnation. *Nature communications,* 3**,** 1293.

REED, M., EVELY, A. C., CUNDILL, G., FAZEY, I., GLASS, J., LAING, A., NEWIG, N., PARRISH, B., PRELL, C., RAYMOND, C. & STRINGER, L. 2010. What is Social Learning? *Ecology and Society,* 15.

REED, M. & KEECH, D. 2017. Making the city smart from the grassroots up: The sustainable food networks of Bristol. *City, Culture and Society, in press*.

REEVES, D. W. 1997. The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil and Tillage Research,* 43**,** 131-167.

REICOSKY, D. C. 2015. Conservation tillage is not conservation agriculture. *Journal of Soil and Water Conservation,* 70**,** 103A-108A.

REYCHAV, I., NDICU, M. & WU, D. 2016. Leveraging social networks in the adoption of mobile technologies for collaboration. *Computers in Human Behavior,* 58**,** 443-453.

RIJSWIJK, K., KLERKX, L. & TURNER, J. 2018. Digitalisation of agricultural knowledge providers: the case of New Zealand. *European International Farm Systems Association Symposium***,** 1-5.

RIVERA-FERRE, M., ORTEGA-CERDÀ, M. & BAUMGÄRTNER, J. 2013. Rethinking Study and Management of Agricultural Systems for Policy Design. *Sustainability,* 5**,** 3858-3875.

ROBINSON, D. A., HOCKLEY, N., COOPER, D. M., EMMETT, B. A., KEITH, A. M., LEBRON, I., REYNOLDS, B., TIPPING, E., TYE, A. M., WATTS, C. W., WHALLEY, W. R., BLACK, H. I. J., WARREN, G. P. & ROBINSON, J. S. 2013. Natural capital and ecosystem services, developing an appropriate soils framework as a basis for valuation. *Soil Biology and Biochemistry,* 57**,** 1023-1033.

ROCHETTE, P. 2008. No-till only increases N2O emissions in poorly-aerated soils. *Soil and Tillage Research,* 101**,** 97-100.

ROCKSTRÖM, J., STEFFEN, W., NOONE, K., PERSSON, Å., CHAPIN III, F. S., LAMBIN, E., LENTON, T., SCHEFFER, M., FOLKE, C. & SCHELLNHUBER, H. J. 2009. Planetary boundaries: exploring the safe operating space for humanity. *Ecology and society,* 14.

ROGERS, E. M. 2003. Diffusion of Innovations, 5th edn. *Free Press, New York.*

ROGERS, E. M. & KINCAID, D. L. 1981. Communication Networks; A New Paradigm for Research. *New York; Free Press*.

ROLING, N. 2006. *Conceptual and methodological developments in innovation*, Centre for tropical agriculture (CIAT)-Africa.

RÖLING, N. & JIGGINS, J. 1994. Policy paradigm for sustainable farming. European *Journal of Agricultural Education and Extension*, 1, 23-43.

ROUTSCHEK, A., SCHMIDT, J. & KREIENKAMP, F. 2014. Impact of climate change on soil erosion — A high-resolution projection on catchment scale until 2100 in Saxony/Germany. *Catena,* 121**,** 99-109.

RÜCKNAGEL, J., GÖTZE, P., KOBLENZ, B., BACHMANN, N., LÖBNER, S., LINDNER, S., BISCHOFF, J. & CHRISTEN, O. 2016. Impact on soil physical properties of using large-grain legumes for catch crop cultivation under different tillage conditions. *European Journal of Agronomy,* 77**,** 28-37.

RÜCKNAGEL, J., RADEMACHER, A., GÖTZE, P., HOFMANN, B. & CHRISTEN, O. 2017. Uniaxial compression behaviour and soil physical quality of topsoils under conventional and conservation tillage. *Geoderma,* 286**,** 1-7.

SAMIEE, S. & REZAEI-MOGHADDAM, K. 2017. The proposed alternative model to predict adoption of innovations: The case of no-till technology in Iran. *Journal of the Saudi Society of Agricultural Sciences,* 16**,** 270-279.

SCHJØNNING, P., ELMHOLT, S., MUNKHOLM, L. J. & DEBOSZ, K. 2002. Soil quality aspects of humid sandy loams as influenced by organic and conventional long-term management. *Agriculture, Ecosystems & Environment,* 88**,** 195-214.

SCHNEIDER, F., LEDERMANN, T., FRY, P. & RIST, S. 2010. Soil conservation in Swiss agriculture—Approaching abstract and symbolic meanings in farmers' life-worlds. *Land Use Policy,* 27**,** 332-339.

SCHNEIDER, F., STEIGER, D., LEDERMANN, T., FRY, P. & RIST, S. 2012. No-tillage farming: co-creation of innovation through network building. *Land Degradation & Development,* 23**,** 242-255.

SCHOLL, P., LEITNER, D., KAMMERER, G., LOISKANDL, W., KAUL, H. P. & BODNER, G. 2014. Root induced changes of effective 1D hydraulic properties in a soil column. *Plant Soil,* 381**,** 193-213.

SCHOUMANS, O. F., CHARDON, W. J., BECHMANN, M. E., GASCUEL-ODOUX, C., HOFMAN, G., KRONVANG, B., RUBAEK, G. H., ULEN, B. & DORIOZ, J. M. 2014. Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: a review. *Sci Total Environ,* 468-469**,** 1255-66.

SCHULTE, R. P. O., BAMPA, F., BARDY, M., COYLE, C., CREAMER, R. E., FEALY, R., GARDI, C., GHALEY, B. B., JORDAN, P., LAUDON, H., O'DONOGHUE, C., Ó'HUALLACHÁIN, D., O'SULLIVAN, L., RUTGERS, M., SIX, J., TOTH, G. L. & VREBOS, D. 2015. Making the Most of Our Land: Managing Soil Functions from Local to Continental Scale. *Frontiers in Environmental Science,* 3.

SCHULTE, R. P. O., CREAMER, R. E., DONNELLAN, T., FARRELLY, N., FEALY, R., O'DONOGHUE, C. & O'HUALLACHAIN, D. 2014. Functional land management: A framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. *Environmental Science & Policy,* 38**,** 45-58.

SCHULTE, R. P. O., RICHARDS, K., DALY, K., KURZ, I., MCDONALD, E. J. & HOLDEN, N. M. 2006. AGRICULTURE, METEOROLOGY AND WATER QUALITY IN IRELAND: A REGIONAL EVALUATION OF PRESSURES AND PATHWAYS OF NUTRIENT LOSS TO WATER. *Biology and Environment: Proceedings of the Royal Irish Academy,* 106B**,** 117-133.

SCHWEN, A., BODNER, G. & LOISKANDL, W. 2011a. Time-variable soil hydraulic properties in near-surface soil water simulations for different tillage methods. *Agricultural Water Management,* 99**,** 42-50.

SCHWEN, A., BODNER, G., SCHOLL, P., BUCHAN, G. D. & LOISKANDL, W. 2011b. Temporal dynamics of soil hydraulic properties and the water-conducting porosity under different tillage. *Soil and Tillage Research,* 113**,** 89-98.

SCHWEN, A., JEITLER, E. & BÖTTCHER, J. 2015. Spatial and temporal variability of soil gas diffusivity, its scaling and relevance for soil respiration under different tillage. *Geoderma,* 259-260**,** 323-336.

SCHWILCH, G., BERNET, L., FLESKENS, L., GIANNAKIS, E., LEVENTON, J., MARAÑÓN, T., MILLS, J., SHORT, C., STOLTE, J., VAN DELDEN, H. & VERZANDVOORT, S. 2016. Operationalizing ecosystem services for the mitigation of soil threats: A proposed framework. *Ecological Indicators,* 67**,** 586-597.

SCOONES, I. & THOMPSON, J. 1994. Beyond Farmer First: rural people's knowledge, agricultural research and extension practice. *Intermediate Technology Publications IIED*.

SCOTLAND, J. 2012. Exploring the Philosophical Underpinnings of Research: Relating Ontology and Epistemology to the Methodology and Methods of the Scientific, Interpretive, and Critical Research Paradigms. *English Language Teaching,* 5.

SCOTT, J. 1988. Trend report. Social network analysis. *Sociology,* 22**,** 109-127.

SEEHUSEN, T., RILEY, H., RIGGERT, R., FLEIGE, H., BØRRESEN, T., HORN, R. & ZINK, A. 2014. Traffic-induced soil compaction during manure spreading in spring in South-East Norway. *Acta Agriculturae Scandinavica, Section B — Soil & Plant Science,* 64**,** 220-234.

SEWELL, A. M., GRAY, D. I., BLAIR, H. T., KEMP, P. D., KENYON, P. R., MORRIS, S. T. & WOOD, B. A. 2014. Hatching new ideas about herb pastures: Learning together in a community of New Zealand farmers and agricultural scientists. *Agricultural Systems,* 125**,** 63-73.

SHARMA, V., IRMAK, S. & PADHI, J. 2018. Effects of cover crops on soil quality: Part I. Soil chemical properties—organic carbon, total nitrogen, pH, electrical conductivity, organic matter content, nitrate-nitrogen, and phosphorus. *Journal of Soil and Water Conservation,* 73**,** 637-651.

SHORT, C., CLARKE, L., CARNELLI, F., UTTLEY, C. & SMITH, B. 2019. Capturing the multiple benefits associated with nature-based solutions: Lessons from a natural flood management project in the Cotswolds, UK. *Land Degradation & Development,* 30**,** 241-252.SIMPLY MEASURED 2014. The Complete Guide to Twitter Analytics. *How to analyze the metrics that matter.*

SKAALSVEEN, K., INGRAM, J. & CLARKE, L. E. 2019. The effect of no-till farming on the soil functions of water purification and retention in north-western Europe: A literature review. *Soil and Tillage Research,* 189**,** 98-109.

SKAALSVEEN, K., INGRAM, J. & URQUHART, J. 2020. The role of farmers' social networks in the implementation of no-till farming practices. *Agricultural Systems,* 181.

SLIGO, F. X. 2005. Informational benefits via knowledge networks among farmers. *Journal of Workplace Learning,* 17**,** 452-466.

SLIGO, F. X. & MASSEY, C. 2007. Risk, trust and knowledge networks in farmers' learning. *Journal of Rural Studies,* 23**,** 170-182.

SMITH, P., ASHMORE, M. R., BLACK, H. I. J., BURGESS, P. J., EVANS, C. D., QUINE, T. A., THOMSON, A. M., HICKS, K., ORR, H. G. & ANGELER, D. 2013. REVIEW: The role of ecosystems and their management in regulating climate, and soil, water and air quality. *Journal of Applied Ecology,* 50**,** 812-829.

SMITH, P., COTRUFO, M. F., RUMPEL, C., PAUSTIAN, K., KUIKMAN, P. J., ELLIOTT, J. A., MCDOWELL, R., GRIFFITHS, R. I., ASAKAWA, S., BUSTAMANTE, M., HOUSE, J. I., SOBOCKÁ, J., HARPER, R., PAN, G., WEST, P. C., GERBER, J. S., CLARK, J. M., ADHYA, T., SCHOLES, R. J. & SCHOLES, M. C. 2015. Biogeochemical cycles and biodiversity as key drivers of ecosystem services provided by soils. *SOIL Discussions,* 2**,** 537-586.

SMITH, P., HOUSE, J. I., BUSTAMANTE, M., SOBOCKA, J., HARPER, R., PAN, G., WEST, P. C., CLARK, J. M., ADHYA, T., RUMPEL, C., PAUSTIAN, K., KUIKMAN, P., COTRUFO, M. F., ELLIOTT, J. A., MCDOWELL, R., GRIFFITHS, R. I., ASAKAWA, S., BONDEAU, A., JAIN, A. K., MEERSMANS, J. & PUGH, T.

A. 2016. Global change pressures on soils from land use and management. *Glob Chang Biol,* 22**,** 1008-28.

SMITH, R. E., CORRADINI, C. & MELONE, F. 1993. Modeling Infiltration for Multistorm Runoff Events. *Water Resources Research,* 29**,** 133-144.

SMITH, V. H. 1983. Low nitrogen to phosphorus ratios favour dominance by blue-green algae in lake phytoplankton. *Science,* 221**,** 669-671.

SOANE, B. D., BALL, B. C., ARVIDSSON, J., BASCH, G., MORENO, F. & ROGER-ESTRADE, J. 2012. No-till in northern, western and south-western Europe: A review of problems and opportunities for crop production and the environment. *Soil and Tillage Research,* 118**,** 66-87.

SOILCARE, 2020. https://www.soilcare-project.eu/en/

SONNEVELD, B.G.J.S. MERBIS, M.D. ALFARRA, A. & ÜNVER, O. and ARNAL, M.A. 2018. Nature-Based Solutions for agricultural water management and food security. FAO Land and Water Discussion Paper no. 12. *Rome, FAO*. 66 pp.

STANLEY, S. 2013. Harnessing social media in agriculture. *A Report for the New Zealand Nuffield Farming Scholarship Trust NZ Nuffield Scholar*.

STATISTA 2018. Number of social media users worldwide from 2010 to 2021. https://www.statista.com/statistics/278414/number-of-worldwide-social-network-users/.

STAVI, I., BEL, G. & ZAADY, E. 2016. Soil functions and ecosystem services in conventional, conservation, and integrated agricultural systems. A review. *Agronomy for Sustainable Development,* 36.

STENMARK, D. 2002. Information vs knowledge: the role of intranets in knowledge management. *System Sciences,* IEEE, Wailuku**,** 928-937.

STOATE, C., JONES, S., CROTTY, F., MORRIS, C. & SEYMOUR, S. 2019. Participatory research approaches to integrating scientific and farmer knowledge of soil to meet multiple objectives in the English East Midlands. *Soil Use and Management,* 35**,** 150-159.

STRUDLEY, M., GREEN, T. & ASCOUGHII, J. 2008. Tillage effects on soil hydraulic properties in space and time: State of the science. *Soil and Tillage Research,* 99**,** 4-48.

SUCHIRADIPTA, B. & SARAVANAN, R. 2016. Social media: Shaping the future of agricultural extension and advisory services. *GFRAS interest group on ICT4RAS discussion paper, GFRAS: Lindau, Switzerland***,** 9.

SULEMANA, I. & JAMES, H. S. 2014. Farmer identity, ethical attitudes and environmental practices. *Ecological Economics,* 98**,** 49-61.

SUTHERLAND, L.-A., MILLS, J., INGRAM, J., BURTON, R. J., DWYER, J. & BLACKSTOCK, K. 2013. Considering the source: Commercialisation and trust in agri-environmental information and advisory services in England. *Journal of Environmental Management,* 118**,** 96-105.

SUTTON, M. A., HOWARD, C. M., ERISMAN, J. W., BEALEY, W. J., BILLEN, G., BLEEKER, A., BOUWMAN, P., GRENNFELT, H., VAN GRINSVEN, H. & GRIZZETTI, B. 2011. The European Nitrogen Assessment. *Cambridge, UK, Cambridge University Press,* Chapter 5**,** 82-96.

SVANBÄCK, A., ULÉN, B. & ETANA, A. 2014. Mitigation of phosphorus leaching losses via subsurface drains from a cracking marine clay soil. *Agriculture, Ecosystems & Environment,* 184**,** 124-134.

TAMBURINI, G., DE SIMONE, S., SIGURA, M., BOSCUTTI, F. & MARINI, L. 2016. Soil management shapes ecosystem service provision and trade-offs in agricultural landscapes. *Proc Biol Sci,* 283.

TAN, Z. X., LAL, R. & WIEBE, K. D. 2005. Global Soil Nutrient Depletion and Yield Reduction. *Journal of Sustainable Agriculture,* 26**,** 123-146.

TAYLOR, S. D., HE, Y. & HISCOCK, K. M. 2016. Modelling the impacts of agricultural management practices on river water quality in Eastern England. *J Environ Manage,* 180**,** 147-63.

TEASDALE, J. R. 2007. Strategies for soil conservation in no-tillage and organic farming systems. *Journal of Soil and Water Conservation,* 62**,** 144A-147A.

THAKUR, D., CHANDER, M. & SINHA, S. 2017. Whatsapp for farmers: Enhancing the scope and coverage of traditional agricultural extension. *International Journal of Science, Environment,* 6**,** 2190-2201.

THOMAS, E., RILEY, M. & SPEES, J. 2020. Knowledge flows: Farmers' social relations and knowledge sharing practices in 'Catchment Sensitive Farming'. *Land Use Policy,* 90.

TIAN, Y., WANG, S., BAI, X., LUO, G. & XU, Y. 2016. Trade-offs among ecosystem services in a typical Karst watershed, SW China. *Sci Total Environ,* 566-567**,** 1297-1308.

TODOROVIC, G. R., RAMPAZZO, N., MENTLER, A., BLUM, W. E. H., EDER, A. & STRAUSS, P. 2014. Influence of soil tillage and erosion on the dispersion of glyphosate and aminomethylphosphonic acid in agricultural soils. *International Agrophysics,* 28.

TOWNSEND, T. J., RAMSDEN, S. J. & WILSON, P. 2015. How do we cultivate in England? Tillage practices in crop production systems. *Soil Use and Management*.

TRACY, P. W., WESTFALL, D. G., PETERSON, G. A., ELLIOT, E. T. & COLE, C. V. 1990. Carbon, Nitrogen, Phosphorus, and Sulfur Mineralization in Plow and No-Till Cultivation. *Soil Science Society of America,* 54**,** 457-461.

TRAN, T. A., JAMES, H. & PITTOCK, J. 2018. Social learning through rural communities of practice: Empirical evidence from farming households in the Vietnamese Mekong Delta. *Learning, Culture and Social Interaction,* 16**,** 31-44.

TRAN, T. A., NGUYEN, T. H. & VO, T. T. 2019. Adaptation to flood and salinity environments in the Vietnamese Mekong Delta: Empirical analysis of farmer-led innovations. *Agricultural Water Management,* 216**,** 89-97.

TØRRESEN, K. S., SKUTERUD, R., TANDSAETHER, H. J. & HAGEMO, M. B. 2003. Long-term experiments with reduced tillage in spring cereals. I. Effects on weed flora, weed seedbank and grain yield. *Crop protection,* 22**,** 185-200.

UGARTE NANO, C. C., NICOLARDOT, B., QUINCHE, M., MUNIER-JOLAIN, N. & UBERTOSI, M. 2016. Effects of integrated weed management based cropping systems on the water retention of a silty clay loam soil. *Soil and Tillage Research,* 156**,** 74-82.

UGARTE NANO, C. C., NICOLARDOT, B. & UBERTOSI, M. 2015. Near-saturated hydraulic conductivity measured on a swelling silty clay loam for three integrated weed management based cropping systems. *Soil and Tillage Research,* 150**,** 192-200.

UK LEGISLATION 2015. The Water Framework Directive (Standards and Classification) Directions (England and Wales) 2015.

ULRICH, S., HOFMANN, B., TISCHER, S. & CHRISTEN, O. 2006. Influence of Tillage on Soil Quality in a Long–Term Trial in Germany. *Advances in GeoEcology,* 38**,** 110-116.

ULÉN, B., ARONSSON, H., BECHMANN, M., KROGSTAD, T., ØYGARDEN, L. & STENBERG, M. 2010. Soil tillage methods to control phosphorus loss and potential side-effects: a Scandinavian review. *Soil Use and Management,* 26**,** 94-107.

ULÉN, B. M. & KALISKY, T. 2005. Water erosion and phosphorus problems in an agricultural catchment—Need for natural research for implementation of the EU Water Framework Directive. *Environmental Science & Policy,* 8**,** 477-484.

UNGER, P. W. & VIGIL, M. F. 1998. Cover crop effects on soil water relationships. *Journal of Soil and Water Conservation,* 53**,** 200-207.

URBANEK, E., HORN, R. & SMUCKER, A. J. M. 2014. Tensile and erosive strength of soil macro-aggregates from soils under different management system. *Journal of Hydrology and Hydromechanics,* 62.

VALUJEVA, K., O'SULLIVAN, L., GUTZLER, C., FEALY, R. & SCHULTE, R. P. O. 2016. The challenge of managing soil functions at multiple scales: An optimisation study of the synergistic and antagonistic trade-offs between soil functions in Ireland. *Land Use Policy,* 58**,** 335-347.

VAN GAELEN, N., VERSCHOREN, V., CLYMANS, W., POESEN, J., GOVERS, G., VANDERBORGHT, J. & DIELS, J. 2014. Controls on dissolved organic carbon export through surface runoff from loamy agricultural soils. *Geoderma,* 226-227**,** 387-396.

VAN GRINSVEN, H. J. M., TIKTAK, A. & ROUGOOR, C. W. 2016. Evaluation of the Dutch implementation of the nitrates directive, the water framework directive and the national emission ceilings directive. *NJAS - Wageningen Journal of Life Sciences,* 78**,** 69-84.

VELTHOF, G. L., OUDENDAG, D. & OENEMA, O. 2007. Development and application of the integrated nitrogen model MITERRA-EUROPE. Task 1 Service contract "Integrated measures in agriculture to reduce ammonia emissions". Wageningen, The Netherlands, Alterra. *Alterra Report,* 1663.1.

VILLARINO, S. H., STUDDERT, G. A. & LATERRA, P. 2019. How does soil organic carbon mediate trade-offs between ecosystem services and agricultural production? *Ecological Indicators,* 103**,** 280-288.

VIRTO, I., IMAZ, M., FERNÁNDEZ-UGALDE, O., GARTZIA-BENGOETXEA, N., ENRIQUE, A. & BESCANSA, P. 2014. Soil Degradation and Soil Quality in Western Europe: Current Situation and Future Perspectives. *Sustainability,* 7**,** 313-365.

VOGEL, E., DEUMLICH, D. & KAUPENJOHANN, M. 2016. Bioenergy maize and soil erosion — Risk assessment and erosion control concepts. *Geoderma,* 261**,** 80-92.

VOULVOULIS, N., ARPON, K. D. & GIAKOUMIS, T. 2017. The EU Water Framework Directive: From great expectations to problems with implementation. *Sci Total Environ,* 575**,** 358-366.

WANG, J. B., CHEN, Z. H., CHEN, L. J., ZHU, A. N. & WU, Z. J. 2011. Surface soil phosphorus and phosphatase activities affected by tillage and crop residue input amounts. *Plant Soil Environment,* 57**,** 251-257.

WASSERMAN, S. & FAUST, K. 1994. *Social network analysis: Methods and applications,* Cambridge University Press, The Press Syndicate of the University of Cambridge.

WAUTERS, E. & MATHIJS, E. 2014. The adoption of farm level soil conservation practices in developed countries: A meta-analytic review. *International journal of agricultural resources, governance and ecology,* 10**,** 78-102.

WENGER, E. 1998. Communities of practice: Learning, meaning, and identity. *New York, NY, US: Cambridge University Press.*

WHITEHEAD, P. G., JIN, L., CROSSMAN, J., COMBER, S., JOHNES, P. J., DALDORPH, P., FLYNN, N., COLLINS, A. L., BUTTERFIELD, D., MISTRY, R., BARDON, R., POPE, L. & WILLOWS, R. 2014. Distributed and dynamic modelling of hydrology, phosphorus and ecology in the Hampshire Avon and Blashford Lakes: evaluating alternative strategies to meet WFD standards. *Sci Total Environ,* 481**,** 157-66.

WICK, A. F., HALEY, J., GASCH, C., WEHLANDER, T., BRIESE, L. & SAMSON-LIEBIG, S. 2018. Network-based approaches for soil health research and extension programming in North Dakota, USA. *Soil Use and Management.*

WOOD, B. A., BLAIR, H. T., GRAY, D. I., KEMP, P. D., KENYON, P. R., MORRIS, S. T. & SEWELL, A. M. 2014. Agricultural science in the wild: a social network analysis of farmer knowledge exchange. *PLoS One,* 9**,** e105203.

WOZNIAK, G. D. 1993. Joint information acquisition and new technology adoption- late versus early adoption. *Review of Economics and Statistics,* 75**,** 438-445.

WU, B. & ZHANG, L. 2013. Farmer innovation diffusion via network building: a case of winter greenhouse diffusion in China. *Agriculture and Human Values,* 30**,** 641-651.

WUEST, S. B. 2015. Seasonal Variation in Soil Bulk Density, Organic Nitrogen, Available Phosphorus, and pH. *Soil Science Society of America Journal,* 79.

YAGETA, Y., OSBAHR, H., MORIMOTO, Y. & CLARK, J. 2019. Comparing farmers' qualitative evaluation of soil fertility with quantitative soil fertility indicators in Kitui County, Kenya. *Geoderma,* 344**,** 153-163.

YANG, X., SUN, W., LI, P., MU, X., GAO, P. & ZHAO, G. 2019. Integrating agricultural land, water yield and soil conservation trade-offs into spatial land use planning. *Ecological Indicators,* 104**,** 219-228.

YOUNG, R. A., ONSTAD, C. A., BOSCH, D. D. & ANDERSON, W. P. 1989. AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. *Journal of Soil and Water Conservation,* 44.

ŠŪMANE, S., KUNDA, I., KNICKEL, K., STRAUSS, A., TISENKOPFS, T., RIOS, I. D. I., RIVERA, M., CHEBACH, T. & ASHKENAZY, A. 2018. Local and farmers' knowledge matters! How integrating informal and formal knowledge enhances sustainable and resilient agriculture. *Journal of Rural Studies,* 59**,** 232-241.

Appendices

Appendix A – Network characteristics

Overview of research questions (RQ) and their links to network characteristics, how characteristics are measured and the relationship to information flows.

RQ	**Network characteristic**	**How the characteristic is measured**	**Relationship to information flows**
Is there a link between farmer network characteristics and implementation of NT?	The role of social networks in providing information about NT.	- Network density - The average total degree - Betweenness centrality - Closeness centrality - Average neighbour degree	- Higher density between members of the network can increase information flow. - The level of interaction between actors in a social network affect information flow.
What are the characteristics of networks of farmers who have adopted NT farming?	Actors in interpersonal networks, mechanisms for networking, formality	- The types of actors within farmer networks (farmers, academia, farmer organisations etc.) and communication intensity (SNA). - Preferred communication forms (e.g. face-to-face, telephone, social media) - Formal or informal relationships (SNA). - NT farmers' acquaintance network.	- Homophily can decrease the amount of new information coming into the network. - Bridging ties increase access to external information. - Bonding ties increase the uptake of new technology.

Who are the influencers?	Influencers and intermediaries	- The in degree (number of incoming edges) - Influence rating by respondents in the SNA. - Nodes in the SNA that connect clusters	- Central actors can increase information flow by spreading information to a larger number of people. - Key players increase information diffusion between clusters.
What are the temporal and spatial dynamics of farmer networks in relation to NT?	Changes in social networks before after NT implementation Geographical distribution of social network (local/regional/ national/global)	- Changes to members of respondents' social network before and after implementation of NT (SNA). - Changes to who respondents were influenced by before and after NT. - Sources of information before and after NT. - Geographical location of members of respondents' social networks (SNA).	- An increasing number of connections in a network increase density and information flow.
What sort of NT knowledge is communicated by farmer networks?	The extent of knowledge communicated within the NT networks. The nature of information within NT networks.	Interview questions: - Level of knowledge? - Tacit or explicit knowledge?	- Bridging of explicit knowledge to tacit forms can make new information more accessible.

Appendix B – Coding categories for analysis

Overview of coding categories used to analyse interview data in NVivo.

Nr.	Codes	Sub-codes
i	Implementation of NT	Knowledge transfer
		Age of adopters
		Information sources under implementation
ii	Information sources	Information from farmer discussion groups
		Farmer to farmer learning
		Social media as information source
		Farmer influencers
		Who interviewed farmers influence
iii	Spatial and temporal dynamics	Spatial dynamics of NT farmer networks
		Temporal dynamics of NT farmer networks
		Contact intensity between farmers in NT network
		Changes in the networks before and after implementation of NT
iv	Network characteristics	Regional and national actors of NT networks
		Global actors of NT networks
		Local actors of NT networks
		The level of knowledge of NT amongst local farmers
		The level of knowledge about NT within the learning network

Appendix C – SNA table

Please name everyone you discuss farming practices and specifically NT (no-tillage) with (they can be in any order and all names will be kept confidential)

Full name	**Occupation/ relationship (if advisers –specify what sort of adviser and state what organisation they work for)**	**Do you have a 'formal' or 'informal' relationship to this person?**	**Is this person situated within or outside the Cotswolds area?** **Can you provide farm name?**	**If applicable, do you know if this person has implemented NT?** **(yes/no)**	**How often are you discussing NT with this person?** **1 = daily** **2 = weekly** **3 = monthly or less**	**What is your main way of communicating with this person?** **1 = face to face** **2 = telephone, 3 = social media** **4 = farmer events** **5 = forums** **6 = other**	**How often does this person seek your advice?** **1 = daily** **2 = weekly** **3 = monthly or less**	**How often do you seek their advice?** **1 = daily** **2 = weekly** **3 = monthly or less**	**How influential would you say they are?** **(Score from 1 to 5, where 1 = highly influential and 5 = not very influential)**	**Did you start communicating with this person before or after you implemented NT?**

Appendix D – SNA interview guide

SNA farmer interviewing guide:

1. Can you tell me about yourself and your farm?

- How long have you been farming?
- Agricultural background
- Are anyone else in your family involved in farming?
- Farm type
- Farm size
- Farming practices
- How representative is it/you for the area?

2. When/why did you implement NT on your farm?

- Have you made any other changes to your practices recently?

3. Who is your farming network? Did it change after you implemented NT?

4. Are you involved in any initiatives (e.g. Innovative farmers, LEAF, local discussion groups, Agri-environment schemes etc.)?

5. How would you describe the level of knowledge about "BMP/NT" in your network?

6. What effects the level of knowledge (e.g. some very well informed farmers)?

7. How do you think the level of knowledge affect the implementation rate of "BMP/NT"?

8. How often do you interact with people in your network?

9. What platforms of interaction do you prefer?

- Social media?
- Discussion groups?

10. Where/who do you ask for advice about farming practices?

11. What is your impression of the soil quality in the area?

12. What is your impression of the water quality in the area?

13. Who do you think are influenced by you? Do you see yourself as a broker of information?

- If yes, in what way?

Appendix E – Twitter interview guide

Twitter paper farmer interview guide:

Interview questionnaire

Farm name/location	
Name (anonymous)	
Occupation	
Age	
Education	
Date	
Farm type (arable, mixed, livestock etc.)	
Farm size	
How long have you been farming?	

	Question		**Comments**
	Reasons for use of Twitter		
1	**How did you learn to use Twitter?**		
2	**Why Twitter?** **What makes twitter particularly suited to sharing information about soil?**		
3	**How do you use social media/Twitter in your farm business?**		
4	**..and what potential impact do you think Twitter can have on your farm business**		

	(e.g. direct contact with consumers, new markets etc.)?		
5	**Do you use Twitter for networking, if so how, if not – why not??**		
6	**Who are your Twitter network?**		
7	**Do you use your Twitter account for both social and business matters?**		
8	**How does it fit in with other methods of getting advice and information about soil? What other ways do you use to get advice or information about soil management?**		
9	**Do you interact and share knowledge with other farmers about soil management on Twitter?** **Any other methods, like farmer discussion groups?**		
10	**Who do you think are influenced by you on Twitter - do you see yourself as a broker of information?** **If yes: Why have you taken this role?**		

	…and who influence you (be specific; list both groups and individuals)?		
11	**How critical are you of the information you receive and share on Twitter? What does it take for you to trust a source?**		
12	**Practical Use of Twitter**		
13	**What hashtags do you use to share and/or follow soil knowledge (e.g. #rootsnotiron #notill #covercrops)**		
14	**Do you find photos useful for interacting/sharing knowledge and if so why?**		
15	**Do you attend discussion forums on Twitter? If so, what is your role (e.g. taking an active part or observing)?**		
16	**Do you ever ask questions or ask for advice on Twitter? What is the response?**		
17	**Do you use Twitter for learning, if so how, if not – why not?**		

	If yes, how relevant do you find this learning compared to non-virtual interaction (face to face)?		
18	**Where else do you receive your information from (other social media etc.)?**		
19	**Does learning on social media impact your choice of practices?**		
20	**Is the use of Twitter for farmer learning likely to increase? Are other forms of social media better?**		
21	**What is your impression of the extent of Twitter usage in rural businesses (in your area and the UK in general)?** **Is it just restricted to a few innovative farmers?**		
22	**What do you think are the main barriers for farmers using Twitter?**		
23	**In what ways has twitter changed the advice landscape? Has it impacted on the role of formal knowledge transfer?"** **How significant is twitter in terms of opening up access to information ?**		

24	**Does Twitter contribute to more innovative farming (on your farm and in general)?**		
25	**Can you list the names of your main sources of information on Twitter (4-5 people)?**		

Appendix F – Statement of contribution

Statement of contribution

A peer reviewed paper published in the *Soil and Tillage Research Journal* titled "The effect of no-till farming on the soil functions of water purification and retention in north-western Europe: a literature review":

Skaalsveen, K., Ingram, J., Clarke, L. 2019. The effect of no-till farming on the soil functions of water purification and retention in north-western Europe: A literature review. *Soil & Tillage Research*, 189, 98-109.

Kamilla was the lead author of this paper and responsible for the design, data collection, analysis and led on writing the paper.

Signed by co-authors:

A manuscript submitted for peer review to the *Journal of Soil and Water Conservation* (revised manuscript addressing reviewers comments has been submitted and is awaiting editorial decision) titled: "Impact of no-till practices on water purification and retention functions of soil:

Skaalsveen, K., Clarke, L. 2020. Assessing the impact of no-till practices on water purification and retention functions of soil: results from a UK case study. *Soil and Water Conservation* (Accepted subject to revisions).

Kamilla was the lead author of this paper and responsible for the design, data collection, analysis and led on writing the paper.

Signed by co-author:

A peer reviewed paper published in *Agricultural Systems* titled: "The characteristics and dynamics of learning and knowledge exchange in no-till farmer networks:

Skaalsveen, K., Ingram, J., Urquhart, J. 2020. The role of farmers' social networks in the implementation of no-till farming practices. *Agricultural Systems*, 181.

Kamilla was the lead author of this paper and responsible for the design, data collection, analysis and led on writing the paper.

Signed by co-authors:

A peer reviewed paper that was published in a special issue of *Soil Use and Management* titled: "The use of Twitter for knowledge exchange on sustainable soil management":

Mills, J., Reed, M., Skaalsveen, K., Ingram, J. 2018. The use of Twitter for knowledge exchange on sustainable soil management. *Soil Use and Management*, 35 (1), 95-203.

Kamilla designed and conducted the farmer interviews, undertook the interview analysis and contributed to the writing of the paper.

Signed by co-authors: