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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Highlights

- No-till practices significantly reduce soil erosion rates.
- Cover crops are important in no-till systems to improve soil structural properties.
- Some beneficial effects of no-till in north-western Europe are less pronounced.
- The effect of no-till on the water related soil functions is still uncertain.

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

Keywords: No-till, zero-till, conservation agriculture, soil functions, water purification, water retention, farming practices, cover crops, soil cover, crop rotation

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, Schulte et al., 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 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

[1] Schulte et al. (2014) also identified the recycling of (external) nutrient inputs as a function: this soil function refers to the capacity of soils to absorb, store and re-release nutrients to crops over time. Generically, this capacity includes all forms of nutrient inputs, including fertiliser inputs and organic nutrient inputs (i.e. animal dung and urine); both those produced on, and imported onto, the farm.

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.

[2] According to the Köpping climate classification.

- 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 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.

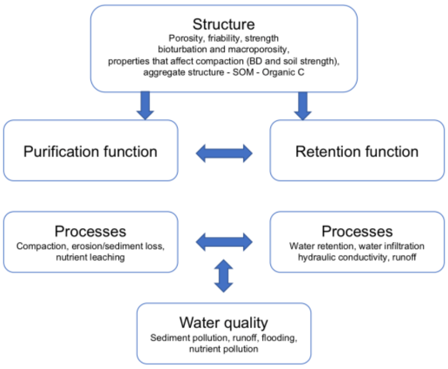


Figure 1 The framework of the review; the effect of soil structural properties on soil water functions and processes influencing water quality.

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).

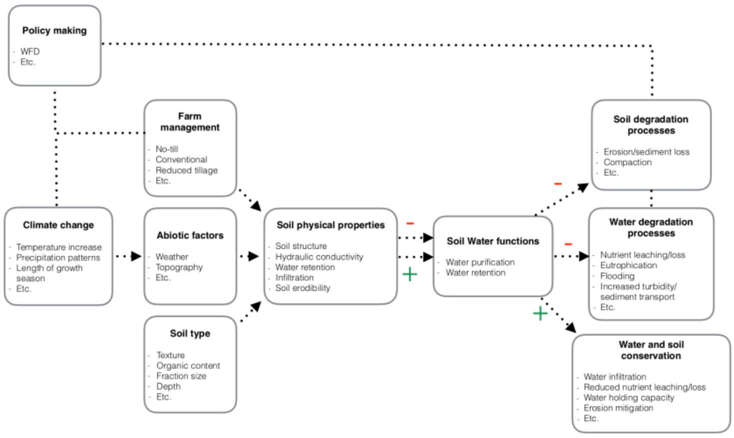


Figure 2 Overview of the effects of soil physical properties on the water purification and retention functions of the soil. The red minus signs represent degradation (i.e. diminished capacity to provide functions) and the green crosses conservation.

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. Rucknagel 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 Rucknagel 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 (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 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, Ugarte 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 to 100% reduction in soil losses, based on three rainfall events with recurrence intervals of 2, 20 and 100 years.

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

	Country	**Soil type**	**Annual precipitation**	**Mean temperature (ºC)**	**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*	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	Rainfall simulation, small scale plots

					natural rainfall simulations	
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 *	463 mm	7.8-9.5	90-100% reduction under NT during rainfall events (2, 20, 100 years return probability)	Modelled data, Erosion-3D

**Classified according to the WRB (IUSS, 2006)*

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, Knapen et al., 2008b, 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, 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. (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 to 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. (2003) 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, Peigné et al., 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, Peigné et al., 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.

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*	1.33*
Constantin et al. (2010)	France	Haplic luvisol**	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*	1.26*
Kechavarzi et al. (2009)	England	Sandy loam soil	1.45	1.47
Moncada et al. (2014)	Belgium	Sandy loam/silt loam	1.32*	1.28*
Schwen et al. (2011)	Austria	Chernozem**	1.34	1.36
Ulrich et al. (2006)	Germany	Sandy loam	1.53	1.57

**These values are presented in mg m^{-3}*

***Classified according to the WRB (IUSS, 2006)*

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, Ugarte 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).

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. (2011)	Austria	Chernozem*	15.9% decrease under NT
Schwen et al. (2015)	Austria	Chernozem*	98.3% decrease under NT
Ulrich et al. (2006)	Germany	Sandy loam	19.8% decrease under NT.

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.

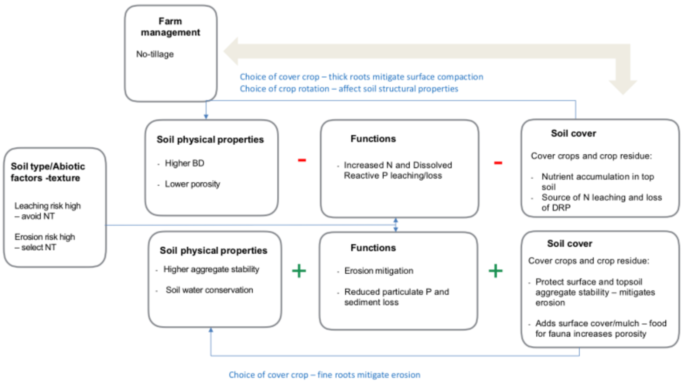
Soil pore structure, an important soil quality variable influencing chemical, physical and biological processes, was often found to be in a poorer state under NT practices than under CT (Garbout et al., 2013, Peigné et al., 2013, Abdollahi et al., 2014, Moncada et al., 2014, Rücknagel et al., 2017). 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 tile drainage (Ulén et al., 2010), meaning that trade-offs have to be made in management decisions.

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., 2008a, Knapen et al., 2008b, Routschek et al., 2014, Van Gaelen et al., 2014, Ugarte 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). 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.

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.

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.

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 Bergström 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).

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.

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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Supplementary material

Overview of search criteria used to select literature for the review.

		No till (zero tillage, direct drilling)	Cover crops (green manuring, catch crops)	Crop residue (mulching)	Crop rotation (intercropping)
Soil structure	Soil structure	"No-till*" OR "Zero till*" OR "direct drilling" AND "Soil structure"	"Cover crop*" OR "Green manur*" OR "Catch crop*" AND "Soil structure"	"Crop residue*" OR "Mulch*" AND "Soil structure"	"Crop rotation" OR "Intercropping" AND "Soil structure"
Water purification	Erosion	"No-till*" OR "Zero till*" OR "direct drilling" AND "Erosion"	"Cover crop*" OR "Green manur*" OR "Catch crop*" AND "Erosion"	"Crop residue" OR "Mulching" AND "Erosion"	"Crop rotation" OR "Intercropping" AND "Erosion"

		No till (zero tillage, direct drilling)	Cover crops (green manuring, catch crops)	Crop residue (mulching)	Crop rotation (intercropping)
	Nutrient leaching/nutrient loss/phosphorus	“No-till*” OR “Zero till*” OR “direct drilling” AND “Nutrient leaching” OR “Nutrient loss” OR phosphorus	“Cover crop*” OR “Green manur*” OR “Catch crop*” AND “Nutrient leaching” OR “Nutrient loss" OR phosphorus	“Crop residue” OR “Mulching” AND “Nutrient leaching” OR “Nutrient loss" OR phosphorus	“Crop rotation” OR “Intercropping” AND “Nutrient leaching” OR “Nutrient loss” OR phosphorus
Water retention	Soil hydrology	“No-till*” OR “Zero till*” OR “direct drilling” AND “hydrology”	“Cover crop*” OR “Green manur*” OR “Catch crop*” AND “hydrology”	“Crop residue” OR “Mulching” AND “hydrology”	“Crop rotation” OR “Intercropping” AND “hydrology”
	Infiltration	“No-till*” OR “Zero till*” OR “direct drilling” AND “Infiltration”	“Cover crop*” OR “Green manur*” OR “Catch crop*” AND “Infiltration”	“Crop residue” OR “Mulching” AND “Infiltration”	“Crop rotation” OR “Intercropping” AND “Infiltration”

	No till (zero tillage, direct drilling)	Cover crops (green manuring, catch crops)	Crop residue (mulching)	Crop rotation (intercropping)
Hydraulic conductivity	“No-till*” OR “Zero till*” OR “direct drilling” AND “hydraulic conductivity”	“Cover crop*” OR “Green manur*” OR “Catch crop*” AND “hydraulic conductivity”	“Crop residue” OR “Mulching” AND “hydraulic conductivity”	“Crop rotation” OR “Intercropping” AND “hydraulic conductivity”
Flood regulation	“No-till*” OR “Zero till*” OR “direct drilling” AND “flood*”	“Cover crop*” OR “Green manur*” OR “Catch crop*” AND “flood*”	“Crop residue” OR “Mulching” AND “flood*”	“Crop rotation” OR “Intercropping” AND “flood*”
Water retention	“No-till*” OR “Zero till*” OR “direct drilling” AND “retention”	“Cover crop*” OR “Green manur*” OR “Catch crop*” AND “retention”	“Crop residue” OR “Mulching” AND “retention”	“Crop rotation” OR “Intercropping” AND “retention”