No-till in northern, western and south western Europe: A review of problems and opportunities for crop production and the environment

Brennan D. Soane[1], Bruce C. Ball[2*], Johan Arvidsson[3], Gottlieb Basch[4], Felix Moreno[5], Jean Roger-Estrade[6]

[1]Crachin, Easter Howgate, Penicuik, EH26 0PE, UK
[2]Scottish Agricultural College, Edinburgh, EH9 3JG, UK
[3]Swedish University of Agricultural Sciences, Department of Soil and Environment, Box 7014, 750 07 Uppsala, Sweden
[4]Univerity of Évora, Crop Science Department, P-7000 Évora, Portugal
[5]IRNAS (CSIC), Avenida Reina Mercedes 10, P.O. Box 1052, 41080 Sevilla, Spain
[6]AgroParisTech, Centre de Grignon, BP 01, 78 850 Thiverval-Grignon, France

---

Abstract

Recent literature on no-till is reviewed with particular emphasis on research results and commercial uptake in northern, western and southwestern Europe. Increased interest in no-till, as well as minimum or reduced tillage, is the result of changes in the economic circumstances of crop production, the opportunity to increase the area of more profitable autumn-sown crops and increased concern about environmental damage associated with soil inversion by ploughing. Highly contrasting soil and climate types within and between these regions exert a strong influence on the success of no-till. While no-till may often result in crop yields which equal or exceed those obtained after ploughing, modest reductions in yield may be tolerated if production costs are appreciably lower than with ploughing. The relative costs of fuel and herbicides have changed appreciably in recent years making no-till more attractive commercially. While effective weed control is an essential aspect of no-till, current herbicide technology may not yet fully achieve this.

No-till soils will usually have lower temperature and higher moisture content at the time of drilling, delaying drilling of spring-sown crops in northern regions. Their bulk density and bearing capacity are greater than for ploughed soils but the pronounced vertical orientation of macroporosity will allow encourage penetration of roots and water, especially in view of the increased population of deep-burrowing earthworms. Particular care must be taken to minimise soil damage at harvest and to ensure the even distribution of crop residues prior to drilling.

Reduced erosion and runoff under no-till are widely observed and are of particular importance in southwestern Europe. No-till reduces losses of phosphorus in runoff and the loss of nitrate through leaching. Emissions of greenhouse gases CO_2 and N_2O from no-till soils are highly variable and depend on complex interactions of soil properties. Emission of CO_2 from fuel during machinery usage is always appreciably reduced with no-till. Increased soil organic carbon in surface layers of no-till soils may not be associated with increased carbon sequestration throughout the profile. All relevant factors must be included in the evaluation of the relative overall climate forcing effects of no-till and ploughing. Adoption of no-till could be encouraged by government financial assistance in recognition of environmental benefits, although future restrictions on the use of herbicides may be a deterrent. Opportunities for further research on no-till are outlined.

*Corresponding author. Tel.: +44 131 535; fax: +44 131 535 4144
E-mail address: bruce.ball@sac.ac.uk

1. Introduction

1.1. Definition of no-till

No-till (also known as direct drilling and zero tillage) is a system in which crops are sown without any prior loosening of the soil by cultivation other than the very shallow disturbance (< 5 cm) which may arise by the passage of the drill coulters and after which usually at least 30% of the surface remains covered with plant residues.

1.2. Geographical and time limits of review

Priority is given to literature published since 2000 but much earlier research work was undertaken in Europe and is considered in previous reviews (Cannell et al., 1978; Basch, 1988; Christian and Ball, 1994; Rasmussen, 1994; Massé et al., 1994; Van Ouwerkerk and Perdok, 1994; Linke, C., 1996; Tebrügge and Böhrnsen, 1997a; Fernández-Quintanilla, 1997; González et al., 1997; Tebrügge and Düring, 1999; Tebrügge, 2001; Mikkola et al., 2005). Although no-till research has been conducted in virtually all parts of Europe, we have concentrated attention on northern Europe (Finland and Scandinavia), western Europe (Netherlands, UK, France and Germany) and southwestern Europe (Spain and Portugal). This provides a transect from a boreal to a Mediterranean climate (Table 1) and covers a wide range of crops and production systems. The average growing season in Finland is limited by frost to May-September (Personal communication: L. Alakukku) while in northern Spain it is limited by shortage of available soil water to October-July (Fernández-Ugalde et al., 2009b).

The climate of much of northern and western Europe is broadly characterised by long, wet winters, late and often wet springs, cool moist summers, and an early return of autumn rains, sometimes before crop harvests have been completed or even commenced. Rainfall intensities are generally low and soil and water conservation problems rarely have a widespread influence on farming practice although, on susceptible soils and sloping ground, erosion can be serious locally as a result of occasional local high intensity rain or wind storms. Interest in no-till in this region has therefore been primarily to reduce costs and to increase area capability rather than the need to reduce soil erosion and runoff. No-till also has the ability to reduce the surface movement into water courses of particulate P and herbicides as pollutants.

These conditions contrast very markedly with those in southwestern Europe (roughly defined as latitudes below 43 ^{o}N) in which much of the summer growing season is hot and semi-arid and rain falls mainly in winter (Table 1), with some summer rain storms which can be highly erosive. In these areas soil and water conservation, with the maintenance of a crop residue mulch on the surface, have assumed a dominant role in the adoption of no-till, especially in seasons of unusually low (<300 mm) or high (>800 mm) annual rainfall (Giráldez et al., 1997). Due to drought cropping in southwestern Europe in summer is often impossible in the absence of irrigation.

The values for water deficit (potential evapotranspiration - rainfall) shown in Table 1 are a useful guide to the likely problems arising with no-till. In northern and western Europe, water deficits during winter are usually negative indicating the high risks of soil anaerobiosis in poorly drained no-till soils. In south western Europe the high positive water deficits during the summer months confirm the benefits to be gained by water conservation opportunities with no-till. However, in some parts of south western Europe winter rainfall, though very unpredictable, may exceed evapotranspiration (Table 1) and soils will suffer from water logging (Basch and Carvalho, 1997).

Table 1
Some climate characteristics (average rainfall, temperature, potential evapotranspiration, water deficit) at representative locations in Europe arranged by latitude.

Location	Country[1]	Latitude (˚ ‘ N)	Average rainfall (mm)			Average temperature (˚ C)			Average evapotranspiration (mm)			Water deficit (mm)		
			Annual	Oct-March	April-Sept	Annual	Oct-March	April-Sept	Annual	Oct-March	April-Sept	Annual	Oct-March	April-Sept
Jokioinen	S Finland	60 19	606	261	345	4.3	-2.2	11.1	n.a.	n.a.	401*	n.a.	n.a.	104*
Uppsala	W Sweden	59 88	544	238	306	5.7	-0.7	12.1	545	35	510	1	-203	204
East Lothian	SE Scotland	55 55	686	426	260	8.5	5.2	11.8	473	70	403	-213	-356	143
Harpenden	SE England	51 48	696	379	319	9.5	5.7	13.2	567	84	483			
Versailles	N France	48 48	585	277	308	10.9	6.0	15.6	761	137	625	176	-140	317
Avignon	SE France	43 57	464	230	234	13.6	8.3	18.9	1082	221	863	618	-9	629
Zaragoza	NE Spain	41 39	391	186	204	15.0	9.7	20.2	1329	342	987	938	155	783
Évora	NE Portugal	38 34	642	494	148	15.6	11.7	19.5	1183	304	879	541	-190	731
Sevilla	S Spain	37 03	504	404	100	17.7	12.8	22.6	1159	292	867	655	-112	767

n.a. = not available, * = May to September only, [1] S = south, W = west, N = north, E = east.

1.3. Present state of no-till in Europe

It is now widely recognised that no-till can offer a number of economic and environmental advantages compared to mouldboard ploughing for the preparation of soils prior to crop establishment (Tebrügge, 2001). The global uptake of no-till in 2009 was 105 Mha, an increase of 233% over the previous 10 years (Derpsch and Friedrich, 2009). However, in spite of extensive pioneering research in Europe on no-till, particularly during the period 1960-1990, the uptake of no-till in Europe is currently very limited (Table 2) compared to its widespread use in crop production throughout North and South America and elsewhere (Derpsch, 1998; Triplett and Dick, 2008; Derpsch and Friedrich, 2009). In view of this, Europe is considered to be a "developing continent" with respect to no-till (Basch, 2005), a view supported by Derpsch and Friedrich (2009) in their survey of no-till world-wide. Nevertheless, this review will show that no-till research is now active in several countries of Europe and that there has also been a recent resurgence of commercial interest. Mikkola et al. (2005) report that the area of no-till in Finland increased rapidly from 1998 to reach 8-12% of the total area of cereals and oilseed crops by 2005 and 13% by 2008 (Alakukku et al., 2009b).

Table 2
Commercial uptake of no-till in some Western European countries in 2007-2008. For sources see references cited in footnotes.

Country	Area of no-till[1] (kha)
Finland*	200
Germany*	5
France*	200
Switzerland*	12.5
Spain*	650
Portugal**	80
Italy**	80
Slovak Rep.**	37

[1]Excluding orchard and tree crops
*Derpsch and Friedrich (2009)
**Basch et al. (2008)

Intermediate forms of non-ploughing or non-inversion tillage have often been adopted more readily than no-till (Cannell, 1985; Tebrügge and Düring, 1999; Munkholm et al., 2006; Morris et al., 2010) and are sometimes recommended as an introductory treatment before starting no-till or, along with ploughing, as an occasional remedial treatment if problems have arisen during a period under no-till. Surveys made in 2003/2004 and reported by IRENA (undated) indicate that the incidence of "conservation tillage" (reduced tillage and no-till) throughout the EU-15 countries varied between <5% in Ireland to 10-40% in Austria, Belgium, Germany, Finland, and France. Particularly rapid increases were noted in Portugal and Germany. We are here concerned primarily with continuous no-till.

1.4. Relative advantages and disadvantages of ploughing and no-till

The relative advantages of no-till and ploughing depend on a large number of aspects, grouped roughly into agronomic and environmental factors (Tebrügge, 2001). The factors most likely to influence the successful uptake of no-till are shown diagrammatically in Fig. 1. The opinions and choices of farmers related to tillage will be dictated primarily by agronomic factors (Table 3), whereas environmental factors will be relevant to general concerns about soil and landscape protection and climate change. Ploughing may continue to be attractive, especially on smaller farms (Morris et al., 2010) and where mixed husbandry of crops and animals is practiced, whereas large arable farms may become increasingly well suited to no-till, as well as to intermediate forms of non-ploughing or non-inversion tillage involving reduced depth or intensity of disturbance (Cannell, 1985, Morris et al., 2010).

Fig. 1. A summary of climate (Sections 1 and 2), crop (Section 2), soil (Section 3) and environmental (Section 4) factors related to the sustainable uptake of no-till within European regions, with relevant sections in the paper identified.

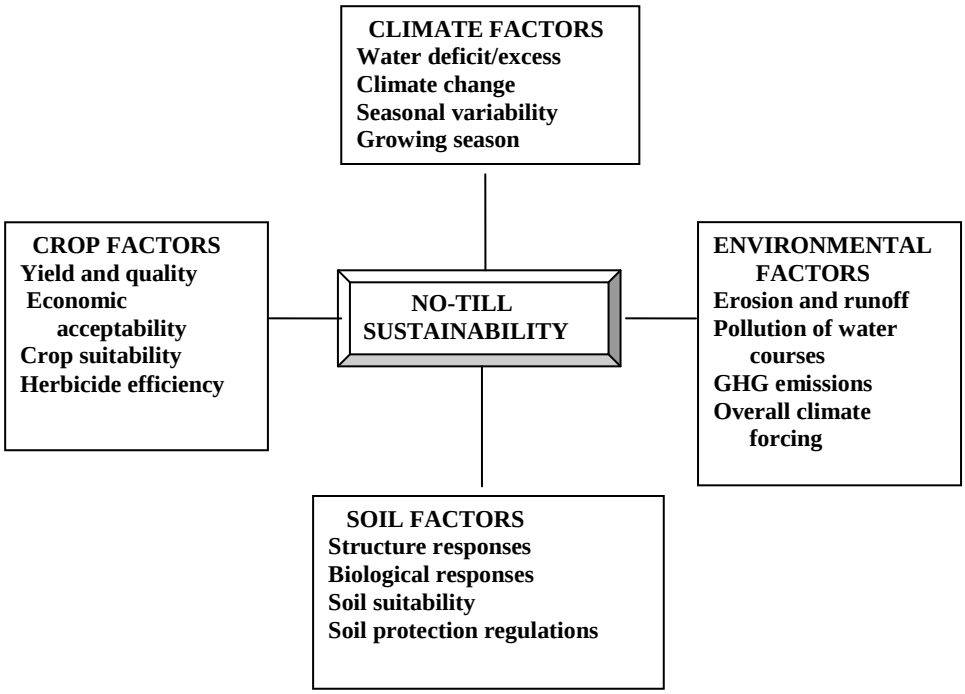


Table 3
Relative agronomic advantages and disadvantages of mouldboard ploughing and no-till in Europe, although not universally relevant to all regions.

Ploughing		No-till	
Advantages	Disadvantages	Advantages	Disadvantages
Appropriate loosening of topsoil prior to seedbed preparation	Pan formation below the depth of ploughing (from passage of plough sole and tractor wheels)	Lack of compaction below plough furrow	Crop establishment problems during very wet or very dry spells
Complete burial of weeds, crop residues, lime, other amendments and manure	Excessive looseness to depth of ploughing	High work rates and area capability	Weed control problems
Inversion allows structural development of lower layers in the topsoil	Exposure of bare topsoil to wind and water Erosion	Increased bearing capacity and trafficability	Cost of herbicides, herbicide resistance
Exposes soil compacted at harvest to loosening by weather	High susceptibility to re-compaction of Topsoil	Reduced erosion runoff and loss of particulate P	Risks of increased N_2O emissions
Increased mixing of nutrients throughout profile	Buried weed seeds brought to the surface	Opportunity to increase area of autumn-sown crops	Reduced reliability of crop yields, especially in wet seasons
Promotes surface drainage leading to warmer, drier seedbed in spring	Reduced trafficability under wet conditions	Stones not brought to the surface	Unsuited to poorly structured sandy soils
Reduced risk of crop diseases	Low work rate and high costs	Drilling phased to take advantage of favourable weather conditions	Unsuited to poorly drained soils
Reliable agronomically in widely differing seasons	Increased CO_2 emissions (fuel and oxidation of SOC)	Increased area capability	Risk of topsoil compaction
		Reduced overall costs (fuel machinery)	Problems with residual plough pans
Preparing a seedbed after grass	Greater oxidation of organic matter near Surface		
			Increased slug damage
	Disruption to macrofauna (earthworms, predatory insects)		
			Unsuited for incorporation of solid animal manures

1.5. Objectives

We review recent literature on no-till research and commercial uptake in northern, western and southwestern Europe and attempt to examine the reasons for the limited current commercial interest in no-till in these regions and to what extent this may be influenced in future by the application of new technology and anticipated changes in economic and environmental circumstances. The problems and opportunities of no-till are examined in the light of recent research findings and farmer experience, with emphasis on crop and soil responses and the environmental implications of adopting no-till in the contrasting climates and soils within these three regions of Europe.

2. Crop production with no-till

2.1. Crop residues and crop establishment

The presence of crop residues on the soil surface is a universal component of no-till now that the burning of residues is no longer practiced in Europe, the only exception being for forage crops for which residues on the surface may be virtually nil. Although the term "crop residues" normally applies to above ground portions of the crop excluding the harvested component, the below ground residues also have an important but often overlooked role in no-till studies.

The quantity of crop residues left on the surface after harvest varies with different crops. Straw yields for cereals are approximately equal to the grain yield, with average straw yields of 6.6 and 6.1 t ha^{-1} for winter wheat and winter barley, respectively in Germany but may reach 10 t ha^{-1} for high yield crops (Ehlers and Claupein, 1994). In a normal year in Denmark the average production of cereal straw is about 3.5 t ha^{-1} (Rasmussen, 1995) whereas Christian and Bacon (1995) report straw residues of 9 t ha^{-1} and Christian and Ball (1994) mention straw yields in England and Wales in 1981 as high as 12.6 t ha^{-1}. Spring wheat and oats were found to have appreciabley larger amounts of crop residues than spring barley and gave problems for no-till sowing subsequently in Finland (Känkänen et al., 2011).

A number of problems have been found in northern Europe when cereal crops were drilled in the presence of crop residues on the surface in contrast to the situation in south western Europe and other semi-arid areas where surface residues serve an essential function in soil and water conservation and promote higher yields (Børresen, 1999). Importance is attached to the amount and form of residues, the height of cut, whether the residues are still attached to the crop roots, and whether still standing (Mikkola et al., 2005). These factors affect the drilling operation and also reduce access of solar radiation to the soil surface and the evaporation of water from the surface. These effects may cause serious delay in the drilling of spring-sown crops as the soil surface may be appreciably wetter and colder than when soils are ploughed prior to winter (Hay et al., 1978), especially in Scandinavia or at high elevations as in Switzerland (Anken et al., 2004). In Finland importance is attached to the moisture content of the soil surface at the time of drilling into no-till soils. If it is high then drilling may have to delayed by up to a week after drilling into ploughed soils is possible, or even several weeks if soils are particularly wet (Mikkola et al., 2005). Such delays are often considered unacceptable by farmers (Van Ouwerkerk and Perdok, 1994). However, delayed crop germination with no-till in some years in Norway has been attributed to a marked reduction of topsoil temperatures under a surface mulch of crop residues (Riley et al., 1994).

Seeds which have been forced into close contact to straw, a problem with some direct disc drills, can suffer from fungal phytotoxicity problems when the surface soil is wet. The results of extensive research on this problem in many parts of the world (reviewed by Morris et al., 2010) has led to the conclusion that drills used in no-till should ensure that crop residues and the planted seed are not in close proximity. Under dry conditions the close proximity of crop residues with seed may delay germination due to lack of seed/soil contact. Although now not practiced in Europe, the burning of crop residues was found to be advantageous in many experiments in the UK (Cannell, 1985) and Scandinavia (Riley et al., 1994) and in practice by many farmers leading to blockage-free drilling operations, reduction in slug infestation, destruction of weed seeds on the surface and improvement in surface tilth. Cedell (1988) presented results from 47 experiments in Sweden with oilseed rape after spring barley 1980-1987. With burning of the straw (28 experiments), crop yield was 13% higher for no-till than for mouldboard ploughing, with removal of the straw 2% higher and with straw left on the soil surface 4% lower. Only in one experiment with burnt straw were crop yields lower with no-till than for mouldboard ploughing, suggesting that on the soils tested compaction was not a major factor affecting yields with no-till. In one long-term experiment on a clay soil, no-till was combined with different straw treatments during the period 1993-2009 (Rydberg, 2010). On average, crop yield for no-till with chopped straw was 16% lower than for mouldboard ploughing. Removing the straw and a shallow stubble cultivation before drilling resulted in the same yield as for mouldboard ploughing. In some areas, cereal straw is used as a source of biomass or, as in Scotland, used for animal bedding and feeding. In such situations stubbles in no-till are cut short and the straw removed prior to drilling (Holmes, 1976; Ball et al., 1994b). Where animal production is not practiced, the residues of no-till cereal crops are best handled by chopping and spreading very evenly (Böhrnsen, 1995; Tebrügge and Böhrnsen, 1997a, Mikkola et al., 2005).

In south western Europe crop yields are generally appreciably lower than in western and northern Europe (see Table 4) and surface residue amounts under no-till will be correspondingly lower. Lampurlanés and Cantero-Martínez (2006) reported that the amount of surface residues plays an important role in soil water conservation under no-tillage in northeast Spain. Thus, when no-till fallow is used, a greater quantity of straw should be left on the soil at harvest of the previous crop to maintain a satisfactory residue cover for moisture conservation during the entire fallow period.

2.2. Crop yields and quality

Intensive research on crop yields with no-till has been conducted in most countries in Europe. An extensive list of quantitative and qualitative indicators comparing no-till with ploughing, based on the results of a large number of research projects, was presented by Tebrügge (2001). Examples of crop yields observed in no-till research in various parts of Europe are summarised in Table 4. In general no-till gives crop yields within 5% of those obtained with ploughing but soil, crop and weather factors exert important influences. Yields of no-till crops tend to approach or exceed those after ploughing as the rainfall decreases from northern to southwestern Europe. For example, in northern Europe no-till yields rarely exceed those after ploughing (Riley et al., 1994; Arvidsson, 2010a) and for spring-sown barley on a clay soil in Finland no-till yields were on average 5% lower than after ploughing (Alakukku et al., 2009b) although in many experiments in Finland no-till yields for spring barley, oats and wheat on clay soils were as low as 60-80% of yields after ploughing (Känkänen et al., 2011). In contrast, within areas of extreme aridity in northern Spain barley yields with no-till were sometimes twice those with conventional tillage (Fernández-Ugalde et al. (2009b).

Table 4
Examples of yields of crops in various locations in Europe.

Reference	Country	Crop	Soil texture (drainage)	No of NT years/ Sites	No-till yield (t ha^{-1})	Ploughed yield (t ha^{-1})	No-till as % of ploughed
Riley et al. (1994)	Norway	Winter wheat, Barley	Various	27/n.k.	5.11	5.17	99
Riley et al. (1994	Sweden	Winter wheat, Barley	Various	22/n.k.	4.45	4.89	91
Arvidsson (2010a)	Sweden	Winter wheat		127	6.26		95
		Barley		44	4.25		88
Alakukku et al. (2009b)	Finland	Spring Barley	Clay Moderate Drainage Vertic Cambisol	1-8	4.1	4.3	95
			Silty clay Well drained Eutric Cambisol	1-7	4.3	4.3	100
Känkänen et al. (2011)	Finland	Spring	Clay Well	1-4	2.5	3.9	65
		Barley	drained	1-4	4.6	5.2	88
		Oats	Vertic		2.4	3.4	72
		Wheat	Stagnosol				
Riley et al. (1994	Denmark	Winter wheat, Barley	Various	80/n.k.	4.54	4.91	92
Rasmussen (1994)	Denmark	Winter Oilseed	Coarse sand	6 y	2.17	2.44	89
		rape	Sandy loam	6 y	3.96	4.13	96
Schjønning et al., (2010a)	Denmark	Winter Wheat	13 % clay	6 y (2003-8)	7.15	8.57	83
Soane and Ball (1998) (3)	Scotland	Spring and Winter barley	Sandy loam (good) Cambisol	24/1	4.82	5.00	96
			Sandy clay loam (moderate) Gleysol	24/1	4.42	4.90	90
Cannell et al. 1986	England	Winter wheat	Clay Stagnogley	1-4/1 (Averag			
			Drained	es over	8.80	8.40	105
			Undrained	4 years)	7.15	7.79	92

Labreuche (1)	France	Maize	Loam Orthic Luvusol	???	8.58	8.37	102
		Wheat			8.79	8.59	102
		Barley			7.92	7.82	101
Basch et al. (1997)	Portugal	Wheat	Various (n.k.)	18/5	1.90	1.95	97
		Barley	Chromic vertisol	4/1	2.14	1.89	113
Lacasta Dutoit et al. (2005)	Spain	Barley	Clay Vertisol	21	2.70	2.62	103
		Sunflower		8	0.94	0.87	108
Fernández-Ugalde et al. (2009b)(2)	Spain	Barley	Silt loam Haplic Calcisol	7	3.50	3.50	100
					2.00	1.00	200

(1) J. Labreuche Personal communication, 2011, Arvalis Institute du Vegetal, Boigneville, France
(2) The higher yields are for 2007 when conditions were wet, the lower yields are for 2008 when conditions were very dry
(3) The upper yields refer to the average over 15 y for Spring barley and the lower yields refer to the average over 9 y for Winter barley

Extensive reviews of crop yields under no-till have been given for the UK by Christian and Ball (1994) (175 experiment years) and for Germany by Tebrügge and Böhrnsen (1997a). In Spain trials of no-till compared to ploughing have been conducted in Andalucía (Giráldez et al., 1985; Pelegrín et al. (1990), in central Spain (Hernánz and Sánchez-Girón, 1981, 1994), and later in other areas of Spain (Cantero-Martínez and Vilardosa, 1993; López and Arrúe, 1994; Cantero-Martínez et al., 1994). Comparative studies of different tillage systems in Portugal, including no-till, started in 1984 in the Alentejo region (Basch, 1988; Carvalho and Basch (1994) and were later were extended to other regions (Basch and Teixeira, 2002). It was concluded that minimum tillage systems, but especially no-till, are capable of providing similar yields.

Mechanisms for yield reductions under no-till vary according to local conditions. On light-textured soils in Denmark, compaction has been identified as the primary problem whereas in Sweden and Norway crop residues generally cause greater problems than compaction while in Finland no-till yield reductions have been attributed to crop residues, weeds and compaction under wet conditions.

Crop yields immediately after adopting no-till are often appreciable lower than after ploughing but improve after about three years of no-till as soil structural conditions improve (Ball et al., 1989; Christian and Ball, 1994; Six et al., 2004; Anken et al., 2006). Christian and Ball (1994) report that winter barley yields during the first year of no-till were 90% of those after 17 years of no-till in the season, whereas the mean yield during the 2nd to 7th years of no-till averaged 98% of yields obtained after 18 to 23 years.

A number of reasons have been advanced to explain frequent conspicuously lower yields after the first one or two years of no-till, when compared to yields after ploughing, than observed subsequently. Among these are: 1) compaction from previous harvest traffic before soil strength and bearing capacity had increased; 2) limited time for build-up of soil structure improving factors under no-till (e.g. accumulation of organic matter, vertically

orientated structure, stabilising influence of roots and fauna; 3) reduced N availability (see Section 2.5); 4) lack of knowledge.

The quality of harvested crops may be of equal economic importance to the yield yet aspects of quality are rarely reported in no-till studies. Stringent quality factors are relevant for grain crops grown for milling, brewing and animal feed (Ball and Davies, 1997). Under partially unsuitable conditions for no-till with spring barley they report that all grain quality indices were significantly lower with no-till than after ploughing. In two seasons grain water content at harvest was respectively 28 and 27 % for no-till and 19 and 21% after ploughing. This large difference would have resulted in an appreciable extra cost for drying the grain from no-till.

2.3. Crop and rotation suitability for no-till

In northern Europe no-till research has mainly concentrated on growing winter wheat, winter- and spring-sown barley. Although spring cereals are the dominant crop in boreal conditions in Finland (Alakukku et al., 2009b), winter-sown crops are generally more suited to no-till than spring-sown crops and no-till has the advantage of allowing these more profitable crops to be established when weather conditions often do not allow opportunity time for conventional ploughing (Soane and Ball, 1998; Mikkola et al., 2005).

Rasmussen (1994) reported results of no-till experiments throughout Scandinavia on soils ranging from 3-4% clay in western Denmark to 60-70% clay in Sweden and Finland. Yield reductions for spring-sown crops were often observed whereas yields of winter-sown crops generally were equal to those after ploughing. Many of these experiments were long-term (>5 years) in which cumulative effects of compaction could be identified and separated from seasonal variation of soil moisture (Rasmussen, 1988; Munkholm et al., 2003).

In northern and western regions there are also considerable areas of other crops grown on wider row widths (mainly potatoes and sugar beet). Potatoes and sugar beet usually require deep and intensive tillage for high yields and their harvest, using heavy machinery, often occurs when soils have returned to a high water content approaching field capacity, causing considerable soil damage. However no-till production of potatoes (Ekeberg and Riley, 1997) and sugar beet (Personal communication: J.Labreuche, (2011), Arvalis Institute du Vegetal, France) may be possible in certain favourable conditions but on less stable soils in the Netherlands reductions in marketable yields of these crops of 20 and 15%, respectively, have been reported under no-till (Van Ouwerkerk and Perdok, 1994), while in Germany.sugar beet under no-till on a Eutric Cambisol with 6% clay yielded 15% less than after ploughing (Tebrügge and Böhrnsen, 1997). The yields of non-graminaceous crops, such as fodder rape, cabbage and potatoes, in southeast Norway all increased in no-till and reduced tillage compared to ploughing on a morainic loam, rich in humus with high gravel and high porosity (Ekeberg and Riley, 1997).

In western Europe the more favourable weather conditions permit additional spring-sown crops such as maize for silage and grain and sunflowers to be grown and in Germany, the yields of field beans, rape seed and maize were equal for no-till and after ploughing (Vogeler et al., 2009). Grassland is an essential crop for many northern and western European countries and the re-seeding of pasture grasses often presents problems which may be avoided by no-till (Van Ouwerkerk and Perdok, 1994). There are also opportunities to establish arable crops after perennial pasture using no-till provided that the soil surface is not

too uneven. Barley yields with no-till were almost equal to those after ploughing a pasture in Finland (Lötjönen and Isolahti, 2010) though in Scotland Vinten et al. (2002) found consistently lower barley yields after grass with no-till than after ploughing due to difficulties in weed control and frequent anaerobic conditions in the soil.

Where rotations are commonly used, the inclusion of a crop unsuited to no-till will make it impossible to gain the advantages of an uninterrupted sequence of no-till operations. However, the use of rotations in no-till cropping has particular relevance for weed control (Jordan et al., 1997). Crops which require much traffic of heavy harvesting machinery, such as potatoes and sugar beet, often when soils are wet in northern Europe, may cause difficulties for no-till establishment of the following crop. However, farmers in Germany and Switzerland are able to plant winter wheat after sugar beet with no-till provided that the previous harvest takes place when soils are not excessively wet.

Crop sequences may influence the choice of crops for no-till. For instance, in France the extension of maize growing to more northerly regions left less opportunity time for ploughing and the drilling of wheat. This favoured reduced tillage after maize before wheat but no-till did not prove so attractive to farmers for technical reasons. More recently trials have been conducted in France to test the suitability of no-till for sugar beet, rapeseed, potatoes, wheat and maize (Massé et al., 1994; Arrouays et al., 2002). Winter wheat, winter barley, rapeseed and peas gave equal or improved yields under no-till but maize and sugar beet showed variable results.

In Germany crops such as legumes, sugar beet, rapeseed and silage maize account for some 30% of the arable land (Tebrügge and Böhrnsen (1997a) and leave very little residue on the surface after harvest and may thus present few problems for drilling subsequent crops provided that soil damage after harvest is not excessive. Winter wheat and rapeseed gave generally equal yield to that after ploughing in Switzerland but silage maize yield after no-till was only 87% of the ploughed yield (Anken et al., 2004).

2.4. Soil suitability for no-till

No-till may be successful on certain soil types and sometimes quite unfavourable on others. Soils in the UK with imperfect drainage and weak structure generally led to lower yields with no-till than after ploughing, especially for spring-sown barley after wet winters. In recognition of the importance of soil characteristics, Cannell et al. (1978) classified the soils of the UK into three classes according to their perceived suitability for no-till and a map was produced showing their distribution. Class 1 soils were most suitable and included the self-mulching calcareous clays derived from limestone or chalk. Later, a Scottish group used a combination of inherent soil wetness and compactability to determine the choice of tillage to be used to establish winter barley in Scotland (Ball, 1986). Throughout the UK good internal drainage was deemed a pre-requisite for reliable success with no-till, as in Germany (Ehlers and Claupein, 1994). On undrained clay soil in England the no-till yield of oats was 3.4 t ha^{-1} compared to 6.1 t ha^{-1} after ploughing. The corresponding yields on drained plots were 7.0 and 7.2 t ha^{-1}, respectively (Cannell et al., 1986). The importance of soil type and permeability for successful no-till is emphasised in wet seasons. On a clay soil in Finland the yield of spring barley was 12% lower for no-till than after ploughing in wet seasons whereas on a silty clay no differences in yield were observed, even in wet seasons (Alakukku et al., 2009b).

Relatively unstable sands, silts, loams and clays, often of marine origin, in the Netherlands were found to be largely unsuited for no-till (Van Ouwerkerk and Perdok, 1994**).** Sandy soils under no-till in the Netherlands showed increased penetration resistance in the 5-30 cm depth due to compaction damage, reducing root penetration and yields, especially of root crops. On weakly structured coarse- textured soils in Denmark soil compaction acts as a severe limitation to the success of no-till. Periodic non-inversion loosening and cautious control of vehicle traffic is recommended for no-till soils (Munkholm et al., 2003). Sandy and sandy loam soils, especially if low in organic matter, may lack the ability to acquire a stabilised structure under no-till, and require regular loosening and are therefore excluded from soils considered to be suitable for no-till in Germany (Ehlers and Claupein, 1994).

2.5. Crop responses to soil nutrients with no-till

The responses of crops to the application and availability of plant nutrients on no-till soils have not been fully examined. Available P and K tend to become highly stratified near the soil surface under no-till but this does not apparently reduce their supply function (Ehlers and Claupein, 1994, Peigné et al., 2007). Enhanced nutrient accumulation near the surface of no-till soils can be due to decomposition of crop residues and to increased microbiological activity. Van Den Bossche et al. (2009) studied the influence of the decomposition of crop residues as a source of nitrogen for crop plants with no-till compared to that of ploughing.

It has been widely observed that during the first 2-3 years of no-till crops require a higher level of N fertiliser to achieve the same level of yield as obtained with ploughing (Frankinet and Roisin, 1989; Ehlers and Claupein, 1994). Possible explanations for this effect are: (a) loss of available N due to denitrification to N_2O (becoming less as structure improves; (b) reduced mineralization of organic matter in spring/autumn/winter (but maybe increased mineralization in summer (Bäumer and Köpke, 1989; Riley et al., 1994); (c) immobilisation of N in crop residues and;(d) limited uptake of soil N due to restricted root growth; (e) compensation effect which overcomes the effects of sub-optimal soil conditions leading to poor establishment (Bäumer and Köpke, 1989; Rasmussen, 1994). After this initial period of no-till there may be opportunities to reduce fertilizer applications which would contribute to reduced overall production costs (Riley et al., 1994).

Response to nitrogen fertilisers in no-till crops vary widely. Ehlers and Claupein (1994) showed that the yield of no-till oats was very much lower at low N applications than the yield for ploughing with no difference at high levels of N application, whereas the responses of winter wheat to applied N were virtually identical for no-till and ploughed treatments at all levels of N application. Massé et al. (1994) claimed that under dry soil conditions the yield of no-till winter wheat at high N applications could exceed those after ploughing as the reduced evaporation of moisture from the no-till soil gave the potential for higher optimum yields. Mean N offtakes by spring-sown no-till cereals on clay soils in Finland were 13-14% lower than for autumn-ploughed soils, even though applied fertilizer-N was 9% higher than on the ploughed soil (Alakukku et al., 2009b). This may have been due to greater denitrification in the no-till soil.

N mineralization from crop residues on or near the surface of no-till soils is slower and N immobilization is greater than when the residues are incorporated by ploughing (Van Den Bossch et al., 2009). These effects, in contrast to the above, have the potential for mineral N content to be higher with less nitrate leaching under no-till giving rise to greater N efficiency, and suggesting that after several years of no-till such soils may need less N fertilisation than

ploughed soils (Regina and Alakukku, 2010). However, urea applied to the surface of no-till soils was found to result in rapid and considerable volatilization of ammonia (Rochette et al., 2009). This was attributed to the 4.2 times higher concentration of urease in no-till than in ploughed soil as well as the crop residues allowing decreased access of the urea to the soil surface. This discourages the surface application of urea on no-till soils. With increasing duration of no-till the amount of potentially minerizable N organic matter will increase which will compensate for the lower mineralization rate (and thus increase N supply to the crop. This is supported by results they reported for responses to N fertilizer in 1972-76 and 1980-81 for oats and winter wheat respectively, with very much higher yields at low N applications being obtained in the earlier period than in the later period in which there was no difference in response for no-till and ploughing.

For spring-sown no-till crops it has been widely considered that a lack of disturbance from cultivations in autumn will reduce nitrogen mineralization and nitrate leaching during the winter (Hansen et al., 2010) while the addition of crop residues to the soil surface will tend to reduce the level of soil mineral nitrogen due to their high C/N ratio encouraging immobilisation. In this way nitrate losses by leaching through the profile at times when the crop is neither present nor actively growing will be reduced (Morris et al., 2010). However, for winter-sown crops nitrate leaching on loamy sand and sandy loams in Denmark was not decreased by no-till or the presence of straw on the surface (Hansen et al., 2010).

2.6. Crop reliability under no-till in variable seasons

There is considerable evidence to show that in northern and western Europe crop yields under no-till are frequently lower than those after ploughing in wet seasons while there may be little or no difference than dry seasons (Riley et al., 1994; Alakukku et al., 2009b). The weather throughout the year will influence soil water content, aeration and temperature and can thus be expected to have a marked influence on crop responses and yields in different seasons. Any lack of yield reliability will strongly influence farmer acceptability of no-till (Morris et al., 2010). Exceptionally wet seasons resulted in reduced yields of spring-sown cereals with no-till on clay soils in Finland (Alakukku et al., 2009b). Over four seasons on a Stagnogley clay soil in England the range of winter wheat yields for drained and undrained ploughed treatments were 54 and 75% of average while the corresponding range of values for no-till were 56 and 110% respectively, confirming that no-till on such a soil would result in very wide yield variation, especially when undrained (Cannell et al. 1986). There are a number of reasons why seasons of high rainfall tend to decrease the success of no-till in northern European conditions. However, difficulties have been found in interpreting the highly important influence of weather conditions on yield results under no-till, even in long-term trials (Soane and Ball, 1998). Apart from the importance of long-term trends in climate, there are often sequences of years in which, for instance, rainfall may be well above or below average rather than following a truly random distribution about a mean. If the duration of an experiment lies mainly within an "abnormal" sequence of weather, the results and their interpretation may be seriously biased.

In Scandinavia very dry spells at the time of sowing in autumn or spring may lead to poor establishment with no-till (Hansen et al., 2010, Schjønning et al., 2010a). During a 6-year period of comparing no-till (NT) with ploughing (CT) on a soil with 13% clay in Denmark, the yield ratio (NT/CT) of winter wheat varied from 55 to 121%, and the variation of NT and CT yields about the mean were 53 and 42%, respectively. This higher variability with NT, plus

the fact that the mean yield with NT was only 84% of the CT mean yield does not encourage commercial uptake of no-till for that location.

In south western Europe no-till can result in an appreciable increase in available soil water in dry seasons. In southern Spain an almost linear inverse relationship has been found between annual rainfall and the ratio of sunflower yield for no-till to that for ploughing. This ratio varied from about 2.5 to about 0.9 for annual rainfalls of 240 and 470 mm, respectively (Giráldez et al., 1997).

2.7. Weeds. diseases and pests

Adoption of no-till introduces important changes to the incidence of weeds, crop diseases and pests, as well as the problem of volunteer cereals (Ball and Davies, 1997; Bräutigam and Tebrügge, 1997; Jordan et al., 1997; Christian and Carreck, 1997). Successful and economic control of these problems is a vital component in ensuring the commercial acceptability of no-till.

2.7.1. Incidence of weeds under no-till

Weed populations under no-till show marked differences from those after ploughing with new or previously unimportant weeds often becoming dominant after a period of no-till in which weed seeds are retained near the surface and their dormancy and germination characteristics will be quite different than if buried during ploughing (Christian and Ball, 1994). Perennial grass weeds (e.g. *Elytrigia repens*) are likely to be favoured by a no-till regime although in Finland *E. repens* is sometimes not a problem on heavy clay soil if there is little infestation initially whereas it normally becomes a serious problem on coarse textured soils (Lötjönen and Isolahti, 2010). Other grass weeds (e.g. *Bromus sterilis* and *Alopecurus mysuroides*) may present considerable difficulties in control due to their unusual reproductive mechanisms. In Scotland after 20 years of no-till the incidence of *Bromus sterilis* in a winter barley crop in ploughed and no-till plots was 2.5 and 59.7 plants m^{-2} respectively (Ball and Davies. 1997). The population of dicotyledenous weeds after no-till are generally similar to that after ploughing and can usually be effectively controlled by herbicides. The situation in southern Europe appears to be different from northern Europe as the long, dry summers restrict perennial weed growth and most of the weed species present are annual (Basch and Carvalho, 1994).

The shading provided by a heavy layer of crop residues with no-till can act as a deterrent for germination of weed seeds on the soil surface as well as inhibiting the early growth after germination of certain weed species on the soil surface. The growth of weed seedlings in spring with no-till winter wheat has been observed to be much slower than on ploughed soils suggesting that herbicide applications could be reduced in such circumstances (Bräutigam and Tebrügge, 1997). A surface mulch of crop residues can also reduce the temperature at or just below the soil surface which may adversely affect weed seed germination (Morris et al., 2010).

Volunteer cereals, causing contamination and reduced quality of harvested grain, can be a problem with no-till in northern and central Europe, especially when winter crops are drilled soon after harvest (Melander, 1998). Ball and Davies (1997) report that volunteer barley in a following winter barley crop for ploughed and no-till land were 70 and 363 plants m^{-2}

respectively. They can often be better controlled by ploughing than by the herbicides used in no-till (Christian and Carreck, 1997).

Many no-till research projects have been conducted with monoculture crop systems which have accentuated weed and pest problems. Rotations and cover crops are considered to be essential components in reducing weed problems and the dependence on herbicide usage in no-till systems (Riley et al., 1994; Ball et al., 1994b; Derpsch and Friedrich, 2009).

2.7.2. Herbicide usage

The availability of herbicides suitable for control of a wide range of dicotyledonous and monocotyledonous weed species is a paramount requirement for any no-till system. The introduction of glyphosate (Roundup) in 1971 brought many advantages but its effectiveness is reduced by low temperatures and frequent rainfall after application and additional herbicides may be needed. In a long-term no-till trial in Switzerland (Anken et al., 2004) the number of herbicides used in addition to glyphosate for maize and wheat were four and eight, respectively.

In south western Europe, weed control under no-till with a pre-emergence herbicide application is effective in years with normal rainfall distribution as most of the weed seeds remain at the soil surface and germinate before the establishment of autumn-sown crops (Calado et al., 2010). Thus, no-till crop establishment also reduces post-emergence infestation as buried seeds remain below the surface soil layer and do not germinate. Furthermore, the reduced weed pressure, together with a much better soil bearing capacity, which allows early herbicide application timings even in wet winters, enables the use of reduced herbicide rates to guarantee effective post-emergence weed control (Barros et al., 2007; Barros et al., 2008). However, a delay of the autumn rains may cause problems through retarded weed germination in already established winter crops. Also the lack of effective herbicides for spring-sown crops in southern Europe (for example, sunflowers and soya) may limit uptake of no-till for these crops.

2.7.3. Herbicide resistance

Herbicide resistance has been identified in several species of grass weeds in the UK such as black grass (*Alopecurus myosuroides*), wild oats (*Avena fatua*), and Italian ryegrass (*Lolium perenne L*) which could threaten the effectiveness of no-till systems dependent on herbicides (Davies and Finney, 2002). Resistance to atrazine, simazine and glyphosate has been widely reported for numerous weed species on no-till farms in the USA (Triplett and Dick, 2008). These problems, if widespread, may reduce the opportunities for adoption of no-till (Morris et al., 2010). There are thus opportunities for improvements in the use of existing herbicides and the adoption of new ones.

2.7.4. Crop pests

In humid climates the maintenance of crop residues on the surface tends to increase the slug population causing appreciable damage to young seedlings in winter-sown wheat and barley (Jordan et ., 1997). The use of mulluscicides may control slug populations but will increase production costs and may adversely affect beneficial soil biota which can play an important part in biological pest control mechanisms which could result in reduced pesticide requirement in no-till cropping (Jordan et al., 1997). The incidence of shoot and root damage in sugar beet by springtails (Onychiurus spp.) is reduced by no-till whereas the incidence of European corn borer (Ostrinia nubilalis) in maize after maize tends to increase with no-till (Ehlers and Claupein, 1994).

2.7.5. Crop diseases

Tillage practices in general have a limited effect on crop diseases (Jordan et al., 1997) although the presence in no-till of a surface layer of crop residues has potential for the carryover of pathogens, such as leaf spot and root diseases from one season to the next (Mikkola et al., 2005) especially when the same crop is grown consecutively. In Scandinavia leaf net blotch (*Pyrenophoros teres*) has increased after no-till (Ulén et al. 2010) but generally increased crop diseases have not been widespread with no-till. In Scotland fungus snow-rot (*Typhula*), which affects winter-sown cereals, was less prevalent after no-till than after ploughing (Ball and Davies, 1997). Infestation by eyespot *(Pseudocercosporella herpotrichoides)* in winter wheat has been found to be appreciable lower with no-till than ploughing after 8 years but no differences were observed after 3 years (Bräutigam and Tebrügge (1997). The concentration of organic matter near the surface seems to suppress some soilborne fungal crop diseases (Ehlers and Claupein, 1994). Similar results were observed for take-all *(Gäumannomyces graminis).* Reduced tillage and no-till resulted in marked decreases in the incidence of clubroot (Plasmodiophora brassicae) in brassica crops in Norway but without explanation (Ekeberg and Riley, 1997).

Jordan et al. (1997) report that the incidence of Barley Yellow Dwarf Virus on winter barley sown after no-till is only 2.7% compared to 57.3% after ploughing. They suggest two explanations, (1) the aphids which spread the virus do not recognise the young barley plants in the presence of residues and (2) the surface soil in no-till will harbour greater numbers of beneficial polyphagous predators (insects and spiders).

2.7. Economics and energy use with no-till cropping

Economics will dictate whether farmers find no-till an attractive alternative to ploughing but the components contributing to the overall decision are complex and research has seldom been undertaken to make a full analysis on a whole farm basis. Some of the relevant factors are listed in Table 5.

Table 5
Factors of relevance in making whole-farm economic comparisons of tillage systems.

Size of farm	Costs of machinery requirements
Role of animals (if any)	Value and use of crop residues
Crop yield expectations (and variability)	Influence on choice of crops
Availability and costs of herbicides	Fuel and labour costs
Rotational practices	Farmer skills and knowledge

With no-till the greater opportunity to grow more profitable winter-sown crops may be an important economic advantage. Tebrügge and Böhrnsen (1997b) surveyed the opinions of 111 farmers in 7 European countries and found that reduced working time and lower costs were the dominant reasons for adopting no-till. Examples of labour, herbicide and mechanization costs for crop establishment by no-till and ploughing (Table 6) given by Crochet et al. (2008) showed the total of these costs for no-till was 50% of that for ploughing.

Table 6
Cost of crop establishment for conventional and the no-till treatments in France (after Crochet et al., 2008).

Tillage system	Labour cost (€ ha^{-1})	Herbicide (€ ha^{-1})	Mechanization[1] (€ ha^{-1})
Plough, cultivate, drill	31	2	134
Spray, direct drill	10	7	67

[1]Mechanisation cost includes equipment depreciation, maintenance and operating cost.

Reduced yields with no-till compared to ploughing are recognised as being acceptable if appreciable reductions in production costs can be achieved. Tebrügge and Böhrnsen (1997a) suggest that yield reductions with no-till up to 12-28% would be acceptable on a 500 ha farm. On 100-150 ha in Finland a yield depression of 10-15% with no-till would be economically acceptable (Mikkola et al., 2005). However, Khaledian et al. (2010) point out that sometimes the economic loss arising from any yield reduction in adopting no-till may well be greater than the reduced costs of production. Yield responses to no-till obtained in experiments may be biased since the quality of management on comparatively small plots may not be achievable in commercial farming (Soane and Ball, 1998; Ball et al., 1994a).

Studies on the economic implications of adopting no-till for winter wheat, winter rape, winter barley, and maize grain over a period of 4 years in the relatively dry, cool climate of northeast Germany (100 km north of Berlin) are reported by Verch et al. (2009) using experimental field data applied to a hypothetical 1000 ha farm and taking into account all relevant expenses. The calculated profit (averaged over crops and a 4-year period) for ploughing, reduced tillage and no-till were -7, 111 and 55 euros ha^{-1} respectively. The negative profit with ploughing arose because of the high costs of land preparation in relation to the prices obtained for crops. Wheat grown with no-till in one year resulted in the highest profit (468 euros ha^{-1}) but large yield variation with no-till in some seasons reduced overall potential profit.

The costs of adopting a no-till system relative to those for ploughing will vary with time. Over the past 30 years the cost of gyphosate relative to the cost of diesel has decreased considerably. Details of savings in fuel consumption obtainable with no-till are given in Section 4.6.2.

3. Soil responses to no-till

3.1. Structure and composition

At the start of no-till experimentation in Europe there was no way of anticipating whether soil quality would improve as a result of increased biological activity and accumulation of organic matter or, on the other hand, deteriorate as a result of cumulative increases in compaction and reduced permeability. There were clear opposing mechanisms for improvement or deterioration of structure. As a result of much research (Ball et al., 1998, Tebrügge, 2001), a range of soil responses can now be anticipated after introduction of no-till (Table 7).

Table 7: Widely reported changes in soil properties within five or fewer seasons of no-till.

Advantages
Increased aggregate stability, especially near surface
Increased organic matter content near surface
Increased vertical and stable pore structure
Increased biological activity, especially earthworms
Increased infiltration rate
Increased hydraulic conductivity in subsoil on well structured soils
Increased soil strength and load bearing capacity with reduced damage from traffic
Disadvantages
Increased bulk density within previous ploughed layer (0-25 cm depth)
Increased moisture content near surface in spring in northern regions delaying drilling
Reduced soil surface temperature, especially in spring in northern regions delaying drilling
Increased acidity near surface
Increased accumulation of P near surface with risks of loss in runoff

The stratification ratio, defined by Franzluebbers (2002) as the ratio of a parameter value in the soil surface with that at a lower depth, may be used as an indicator of soil quality. Such indicators of soil quality were studied in long-term tillage studies in Spain by Imaz et al. (2010). The most sensitive indicators were penetration resistance, particulate organic matter (POM), total organic matter and aggregate stability for the 0-5 and 5-15 cm layers. These factors were all positively correlated to soil water retention, earthworm activity and organic matter stratification, which were all greater with NT than with conventional tillage. The percentage of water resistant aggregates (at 0-20 cm, averaged for three crops over 6 years) for a clay loam soil in the Czech Republic was 27.8 % for ploughed soils and 45.9% for no-till (Javůrek and Vach, 2009).

An accumulation of organic matter near the surface after a relatively short period of no-till was widely reported in early experiments (Ball et al., 1998) and subsequent development of vertically oriented soil structural characteristics are attributed to increased earthworm population, increased aggregation, stability of old root channels, and natural pedological activity due to shrinkage and swelling in clays rich in montmorillonite. Such soils are essentially self-mulching, especially when calcareous. No-till also results in soils gaining bulk density, mechanical strength and aggregate stability. These cumulative effects, with an equilibrium usually not being reached in less than three years (Soane and Ball, 1998), mean that extrapolation from the results for the first year or two of experiments may be highly misleading. The accumulation of organic C near the surface of no-till soils is matched by a similar accumulation and stratification of total N.

Long-term adoption of conservation tillage (reduced and no-tillage) in Mediterranean areas of Spain has proven to be an effective way to increase soil organic matter and, especially, to improve biochemical quality at the soil surface (Madejón et al., 2009). Changes in soil biochemical properties, and their distribution with depth, with conservation tillage will complement physical and chemical tests to evaluate the effect of conservation tillage in Mediterranean semi-arid conditions. Madejón et al. (2009) have shown the importance of the stratified characteristics of the total organic carbon (TOC) with depth since the climatic

conditions of the semi-arid Mediterranean areas are an important limiting factor for the accumulation of organic carbon in the topsoil layers.

3.1.1. Structure orientation

The development of increased vertical orientation of macro-porosity (30-300 µm) is an important characteristic of no-till soils. This arises, partly from the preservation of root and earthworm channels and partly from natural structure development in a vertical orientation in the absence of disruption from ploughing. Vertically orientated macro-porosity with no-till gives rise to increased air and water permeability throughout the profile even when the differences in macroporosity volume show little differences (Vogeler et al., 2009).

3.1.2. Rate of structural change

Changes in some structural properties after the introduction of no-till may be measurable within a few months (bulk density, soil strength) but may not be fully developed for 3-5 years or longer. After the introduction of no-till on loess soil in Germany, the increase in organic C content in the 0-30 cm layer continued until a maximum was reached at 8 to 10 years (Ehlers and Claupein, 1994). Munkholm et al. (2003) found that on a sandy loam in Denmark, bulk density and penetration resistance below 4 cm were appreciably higher for no-till than ploughed soil within the first year and further increased during the second year but differences remained stable after three years. Initial increases in bulk density near the surface of no-till soils may subsequently (after 6 years) decline to values equal to or even less than that after ploughing (Vogeler et al., 2009).

3.2. Changes in soil acidity

Increases of acidity in surface layers of soils under no-till have been widely reported and are usually associated with the acidifying effect of nitrification of ammoniacal fertilisers and the decomposition of crop residues. On well-drained morainic loam in Norway, the pH of topsoil (0-5 cm) after 13 years of no-till was 6.25 compared to 6.48 for ploughing and the lime requirement to rectify this was estimated to be 130 kg CaO ha^{-1} y^{-1} (Ekeberg and Riley, 1997). Such increases of acidity are approaching the levels at which reductions in the availability to crops of soil N, P and K would occur. Reductions in pH may also occur on alkaline soils in south western Europe. For instance, after 6 years of no-till on a vertic Cambisol in Portugal a drop in pH from 8.1 to 7.5 was found for the 0-10 cm depth (Carvalho and Basch, 1995).

3.3. Soil hydrology

After the introduction of no-till, changes can be expected in evaporation of water from the surface, infiltration rate and hydraulic conductivity as a result of the different soil physical properties, particularly increased organic matter near the surface and increased vertically orientated macrostructure throughout the profile (Strudley et al., 2008).

3.3.1. Infiltration

The infiltration rate of no-till soils is usually, but not always, found to be appreciably higher than in ploughed soils. Infiltration rate increases have been observed and have been attributed to protection by residues of the surface from raindrop impact, the stability of aggregates near the surface and continuity between the surface and the sub-surface layers of vertically orientated macroporosity (Ehlers and Claupein, 1994; Ehlers, 1997). Infiltration rate may increase with time after adoption of no-till, along with markedly higher values on

no-till than on ploughed soil (Vogeler et al., 2009). These effects are usually attributed to the greater aggregate stability, SOC and protective mulch normally found on no-till soils (Lampurlanés and Cantero-Martínez, 2006). However, infiltration rate depends closely on the permeability of the surface few mm and the connectivity of pores in that layer with that of lower layers. The continuity of earthworm burrows from the surface to the subsoil under no-till contributes to increased infiltration and reduced runoff. Any type of "pan" or crust at the surface of a no-till soil, perhaps induced by wheel traffic when the surface layer was wet or by raindrop impact when the surface mulch was incomplete, will much reduce the infiltration rate (Armand et al., 2009). After 18 years of no-till on silt loam soil in Poland, Lipiec et al. (2006) found that the cumulative infiltration for no-till was reduced by 61% of the corresponding value for ploughed soil. The greater infiltration on the ploughed soil correlated to greater pore continuity than in the no-till soil. This unusual result, which they attributed to a stable aggregate structure and optimum moisture conditions at the time of tillage, illustrates the variability of conditions found in no-till soil. To gain more appropriate infiltration data, measurements on no-till soils may have to be sited in relation to the horizontal distribution of mulch, surface soil exposure, and any evident wheel tracks (Armand et al., 2009).

3.3.2. Water retention

After 6 years of no-till on a silty loam soil in Germany, differences in water retention between no-till and ploughed land were very small and crop yields were identical (Vogeler et al., 2009). However, in the semi-arid climate of northeastern Spain, the much higher barley yields under no-till (2000 kg ha^{-1}) than conventional tillage (1000 kg ha^{-1}) in dry years is attributed by Fernández-Ugalde et al. (2009b) to the ability of no-till to increase plant available water (held between -33 and -1500 kPa). Plant available water at 0-5, 5-15 and 15-30 cm was 11.7, 18.1 and 26.6 m^3 $100m^{-3}$ for no-till and 7.9, 14.8 and 20.9 m^3 $100m^{-3}$ for soil chisel-ploughed to 15 cm.

3.3.3. *Permeability and deep drainage*

After a preliminary period of establishment, the vertically orientated structure and stabilised earthworm and root channels in no-till soils contribute to increased hydraulic conductivity. Measurements of hydraulic conductivity after 8 years of no-till on a silty loam soil in Germany were higher than after ploughing (Vogeler et al., 2009). Increased downward movement of water under no-till and decreased runoff during periods of high rainfall may result in water tables being higher and oxygen concentrations being lower than for ploughed soils under certain circumstances (Basch and Carvalho, 1997).

3.4. *Damage to un-cultivated soils from vehicle traffic*

In the absence of any loosening from tillage, the physical properties of the topsoil after a period of no-till will be influenced by the passage of loaded wheel or tracks, particularly during harvesting operations. The amount of damage during such traffic is a product of the soil bearing capacity (or compactability) and the mechanical characteristics of the tyres or tracks. Excessive compaction of topsoil is considered a major problem in adoption of no-till in Denmark (Munkholm et al., 2003). Soils under no-till may show the influence of residual ploughpans attributable to the passage of the ploughshare and in-furrow tractor wheel traffic prior to the adoption of no-till. If not loosened prior to commencement of no-till this effect

may still be observed even after 5 years from the cessation of ploughing (Capowiez et al., 2009) and will influence crop and soil responses to no-till.

3.4.1. Bearing capacity and strength

No-till soils initially will be readily compacted and will, within a year or two, show appreciable higher bulk density and strength (penetration resistance) as a result of vehicle traffic and have a much greater bearing capacity than ploughed soils (Tebrügge and Wagner, 1995; Ehlers, 1997). This effect usually occurs throughout the depth at which loosening would have occurred during ploughing (Boguzas et al., 2006).

Unless very wet, no-till soils may show an elastic non-compactive behaviour at normal levels of loading and after a number of years acquire some of the properties of grassland soils with a high bearing capacity (Ehlers and Claupein, 1994). However, periods of high soil moisture and much reduced bearing capacity occur quite frequently in northern and western Europe at the time of harvest for several crops, particularly late harvested sugar beet, potatoes and silage maize. During such periods soil compaction on no-till and very shallow cultivated soils may be considerable and subsequent ploughing may be necessary to achieve maximum crop yield (Koch et al., 2008).

3.4.2. Amount and nature of traffic over no-till soils

Tebrügge and Wagner (1995) showed that the amount of traffic employed for crop establishment (expressed by driving distance per ha, % area covered and load index) is appreciably greater for a ploughed than a no-till system. Wheel traffic of heavy machinery over moist, uncultivated soils, especially at harvest of crops such as maize, sugar beet and potatoes, and of cereals in wet autumns, can cause substantial compaction to a depth of 20-30 cm and sometimes deeper. The risks of serious soil damage at depths up to 30 cm during sugar beet harvesting was demonstrated by Koch et al. (2008) after ploughing and shallow cultivation using a 6-row self-propelled harvester with a total weight of 34-40 t and wheel loads of 7.9 to 11.7 t. Although a no-till treatment was not included, it seems very unlikely that a no-till soil could resist such loading without damage.

There may also be considerable churning and rutting of surface soils at harvest, leaving some areas of fields prone to flooding. These conditions, more prevalent in northern Europe, may render a soil quite unsuitable for subsequent no-till drilling and have tended to promote a "vicious cycle of ploughing-compaction and more ploughing" (Lal, 2001). However, a period of no-till may appreciably increase the trafficabilty of some wet soils through the maintenance of vertically orientated macroporosity (Tebrügge, 2001), and thus reduce soil damage at harvest. If the surface is level the high strength of no-till soils can allow faster drilling.

In spite of the benefits of increased organic matter near the surface, a prolonged regime of no-till in humid climates renders the surface soil liable to suffer from repetitive loading from vehicle traffic. Ball and O'Sullivan (1982) found that soil strengths near the surface of no-tilled soils in the UK were high enough to restrict root growth and seedling emergence. The effect on winter barley grain yield of different numbers of wheal passes over no-till and ploughed soil (Campbell et al., 1986) showed that yield depression at 4 and 6 passes was

less for no-till soils than for ploughed soils suggesting that the no-till soil was more resistant to damage from heavy traffic than ploughed soils.

There is a continuing trend for farm machinery to become larger and heavier especially for harvesting equipment, with the weight of sugar beet harvesters reaching 60 tons. The loads imposed by potato and sugar beet harvesters, with contact pressures often in excess of 200 kPa, are highly damaging, in spite of the use of dual or wide, low pressure tyres. In western Norway potato harvesting operations have to be followed by remedial deep ploughing to avoid erosion risks due to soil impermeability (Ulén et al., 2010). The harvesting of silage maize in Switzerland caused structural damage to the topsoil of a Luvisol when under no-till which was not relieved by natural regenerative processes and resulted in anaerobic conditions during periods of high rainfall and greatly reduced yield relative to ploughing (Anken et al., 2006).

The use of any form of traffic control for sowing, spraying or at harvest is even more appropriate under no-till than under ploughing, especially on soils prone to wetness (Christian and Ball, 1994). Tramlines are now widely adopted as a means to control post-drilling traffic distribution in cereals. Wide-frame tool carriers running on permanent "wheelways" or modular controlled traffic farming (CTF) systems to reduce soil compaction may have particular relevance under no-till systems. Several experiments on traffic-free systems have shown appreciable added benefits in terms of soil quality, crop yields and soil biota where no-till has been employed rather than ploughing (Campbell et al., 1986; Chamen et al., 2003; Tullberg et al., 2007). The adoption of combined no-till and controlled traffic farming has become the norm in certain parts of Australia (Personal communication: J.Tullberg) but CTF systems have a number of problems still to be elucidated in Europe (Schjønning et al., 2010b).

No-till crop production is not necessarily excluded on farms having an animal component but there will be additional risks of soil damage due to vehicle traffic during the distribution of slurry and solid manure and also from animal grazing, especially in northern regions where high soil moisture levels may be common during winter months. In Denmark slurry distribution is commonly undertaken using a tractor/trailer system having a combined weight as high as 50-55 t with axle lads of 13-15 t which would be expected to cause appreciable compaction in the subsoil as well as throughout the topsoil (Schjønning et al., 2010b). It seems unlikely that such a system would be appropriate within a no-till regime. Hansen et al. (2010) report that slurry was applied on no-till soils by trailing hoses over winter cereals and was injected prior to sowing of spring crops. Both operations represent additional wheel traffic over no-till soils when, because of high moisture content, they are liable to be readily damaged. The application of slurry on no-till coarse textured soil in Finland often resulted in lower barley yields with no-till than after ploughing (Lötjönen and Isolahti, 2010). This was partially attributed to ammonia volatilization due to lack of incorporation with the topsoil which could be overcome by using a slurry injector or shallow cultivation.

3.5. Soil biodiversity

In addition to soil microbial activity, soil macro-, meso- and micro-fauna are now recognised as important components in soil health and no-till regimes have widely been found to increase the biodiversity of soils (Ball et al., 1998).

3.5.1. Microbial population and activity

No-till affects the habitat and activity of a large range of soil micro-flora and -fauna and enzyme concentrations. Brito et al. (2006) report that in a Mediterranean climate the roots of wheat plants grown under no-till had a 6-fold greater level of mycorrhizal colonization than did those grown under a ploughing regime. Javůrek et al. (2006) studied the distribution of microbial biomass, number of bacteria, azotobacter, dehydrogenase, urease, invertase, and oxidizable C over a 5-year period after 10 years of no-till and ploughing. Microbial biomass and enzyme activity of β-glucosidase and urease have all found to be higher on silt loam no-till soils in Belgium than on ploughed soils (Van Den Bossche et al., 2009. The value of soil respiration rate as an index of microbial activity in no-till soils was reviewed by Ball et al. (1998). At shallow depths higher microbial activity in no till soils is associated with higher SOC, while at deeper depths the causative factor may be greater earthworm activity.

3.5.2. Earthworms and other macro-fauna

Earthworm populations are invariably higher under no-till than under ploughing and increase with the duration of no-tillage (Gerard and Hay, 1979; Kladivko, 2001; Tebrügge, 2001; Anken et al., 2004; Boguzas et al., 2006; Pelosi et el. 2009; Peigné et al., 2009). In Italy and Germany the numbers of earthworms was found to be up to 8 times higher after a period of no-till while total earthworm biomass was 38 and 176 g m^{-2} for ploughing and no-till, respectively (Ehlers and Claupein, 1994). Significant differences are found in the species and habits of earthworms. In Italy the proportion of *Allolobophora spp.* and *Octodrillus spp.* were much greater than in Germany (Ball et al., 1998). In a three-year experiment northern France, Pelosi et al. (2009) found deep burrowing anecic earthworms were 3.75-fold more numerous in the no-till treatment, while endogeic species were 2.82-fold more numerous in the conventional treatment. After a period of no-till, the anecic group make a major contribution to improvements of soil structure, particularly infiltration and hydraulic conductivity. Species of earthworms feeding on surface residues and living near the surface may be strongly influenced by the type and amount of residues and by the type of direct drill employed (Baker et al., 1996).

The casting activity of earthworms below the soil surface contributes to greater aggregate stability, especially at about 12 cm depth in no-till soils (Bottinelli et al., 2010. Melero et al. (2009) have shown that long-term soil conservation management (reduced and no-tillage) in southern Spain improved the quality of Entisols and Vertisols through enhancing the soil organic carbon fraction and soil biological status, especially in the upper layers. These changes are of great importance to organic matter turnover and nutrient availability under semi-arid Mediterranean climatic conditions and can have a major influence on the upward and downward movement of water, gases and chemicals, the growth of roots and the metabolism of soil biota. Earthworm populations and their effects on macrostructure are best studied in long-term experiments (Peigné et al., 2009).

Under semi-arid Mediterranean conditions in Tunisia quadrat sampling after 3-5 years of no-till after ploughing showed that the number of species of invertebrates increased from 26 to 34 species and that the total population numbers increased from 61 to 319 individuals (Errouisi et al., 2011). In particular, the protected environment of the no-till soil encouraged major increases in the numbers of earthworms and arthropods and hence contributed to enhanced breakdown of organic matter.

The populations of beetles and a wide range of other soil fauna (Derpsch and Moriya, 1998) are associated with the stabilised structure of no-till soils, the greater SOM and

moisture content near the surface and the lack of destruction of bio-structures such as nests, channels, fungal hyphae networks and pathways which occurs with a ploughing regime (Triplett and Dick, 2008). The numbers of beetles was found to increase under no-till in Scotland (Ball et al., 1998).

4. Environmental effects of no-till

4.1. Increased importance of environmental factors

No-till has been found to have a number of environmental advantages in certain circumstances (Düring et al., 1998) which are not necessarily directly related to the immediate economic factors which influence commercial uptake. Nevertheless, they are likely to have increasing importance as concerns about soil and landscape protection assume greater significance. Of particular importance are herbicide dispersal, erosion, P dispersal, eutrophication, nitrate leaching and greenhouse gas emissions (Davies and Finney, 2002).

4.2. Environmental consequences of herbicide usage

4.2.1. Opportunities for reducing herbicide use

The widespread dependence of no-till on high and regular applications of herbicides has raised apprehension as to the fate of applied herbicides and the environmental consequences. Herbicide usage should be reduced to the minimum consistent with desired level of weed control. Split applications may be more effective than a single application of the same amount. In France, following the publication of "Grenelle de L'Environnement", there is a national programme with the objective of reducing herbicide use by 50% by 2018 and there are various possibilities The weed seed bank on the soil surface can be reduced by employing a chaff catcher below combine harvesters and occasional remedial tillage operations may overcome certain weed species which have become dominant after several years of no-till. Herbicide usage can be minimised by the greater use of suitable crop rotations.

4.2.2. Herbicide dispersal and degradation in no-till soils

Gyphosate, the most widely used herbicide in no-till systems, has a low ecotoxicity (Düring and Hummel, 1997) and is usually strongly absorbed on contact with soil and is then subject to microbial degradation but adsorption on to soluble humic acids may result in some leaching within profiles. Herbicides are more actively biodegraded during summer in no-till soils than in ploughed soils due to a greater quantity and activity of microorganisms and increased organic matter near the surface after no-till (Düring et al., 1998).

The widespread use of glyphosate in no-till practice would not seem to present an environmental problem but other herbicides are less strongly adsorbed, and the presence of large macropores in no-till soil profiles may increase the risk of herbicide leaching (Greener et al., 2007). Studies on the transport and persistence of herbicides in soils under conservation tillage (reduced tillage and no-till) in Spain (Cox et al., 1996, 1999; Cuevas et al., 2001) showed that the mobility and persistence of certain herbicides (e.g., trifluralin and metmitron) were lower under conservation tillage than under conventional tillage.

Herbicides may enter water courses both by seepage in ground water and by transfer adsorbed on to soil particles and leaving fields through water or wind erosion. In France, Réal et al. (2004) analyzed the presence of many pesticides in field drainage networks in four

areas of France. They found that when persistent herbicides and fungicides were applied in spring to maize and wheat respectively, the transfer by drainage in winter was less after no-till than after ploughing. Basch et al. (1995) measured the concentrations of atrazine, metolachlor and isoproturon in runoff in Portugal. With the exception of the first runoff event, the amount of herbicides in the runoff from conventional tillage was always higher than in the runoff under no-till and the time between application and the first heavy rain is crucial for the risk of herbicide dissipation in runoff, especially under no-till where a considerable proportion of the herbicide is retained in the surface residues. Similar results were found at other experimental sites in Europe which participated in an EU project on "Effects of tillage systems on herbicide dissipation" (Borin et al., 1997) but there is a need to recognise the widely differing amounts of herbicides used in no-till and ploughing systems.

4.3. Erosion and runoff

Erosion and runoff have been identified as important problems throughout Europe needing control, especially in the Mediterranean region (Düring et al., 1998; Montanarella, 2006; Cerdà et al., 2009), although the intensity is generally appreciably less than that experienced in North and South America and the tropics and erosion was not an incentive for adopting no-till in the Netherlands (Van Ouwerkerk and Perdok, 1994). Recent studies, however, suggest that risks of erosion and compaction of European soils have increased as a result of continuing conventional inversion tillage, reductions in soil organic matter and increased mechanisation (Tebrügge, 2001). Erosion risks may increase with anticipated changes in climate throughout Europe, with a greater number of high intensity rainstorms and a greater likelihood of severe off-site pollution problems from silt, hericides and nutrients conveyed into water courses and other places. Flood control is an increasing concern in many areas and the maintenance of crop residues on the surface of no-till soils of good structure may offer a successful way of reducing runoff during storms.

Troeh and Thompson (1993) estimate that the average annual soil loss within the EU is 17 t ha^{-1} yr^{-1}, considerably exceeding the rate of soil formation of 1 t ha^{-1} yr^{-1}, while losses of 20-40 t ha^{-1} may occur in individual storms (Montanarella, 2006). The soil lost in erosion with no-till at a site in Finland (Puustinen et al., 2005) was 29% of that with ploughing (570 instead of 2100 kg ha^{-1}). Average runoff in Scandinavia, under current traditional tillage practices, varies greatly from 270 mm y^{-1} in Denmark to about 580 mm y^{-1} in Norway. No-till in place of autumn ploughing on sloping clay soils in western Norway, where runoff may sometimes exceed 1000 mm y^{-1}, can reduce particle erosion by 79% (Ulén et al., 2010).

Wind erosion can be a problem on cultivated sandy soils in the Netherlands and some other countries. No-till could overcome that problem but might result in a loss of crop yields on unstable soils (Van Ouwerkerk and Perdok, 1994). Both water and wind erosion are major problems in the Saxony region of Germany and have been found to be effectively controlled by conservation tillage and no-till (IRENA, undated). The increase in soil erosion in northern France is attributed to intensive cultivation practices (Massé et al., 1994) but no-till has not been adopted there to any extent to counter this problem.

Evidence for reduced runoff from no-till soil compared with ploughed soil has been reviewed by Armand et al. (2009) and compared to observations made at two sites in the Upper Rhine valley where runoff typically occurs from maize fields between the end of April and July. They attached importance to the type of management of crop residues and the

lateral distribution of crop residues over the surface of no-till fields which may be far from uniform, strongly influencing the incidence of surface crusting and runoff.

In southern European countries such as Italy, Spain and Portugal, soil and water conservation have also been found to be enhanced by the surface residue mulch with no-till due to increased infiltration during winter rainfall and reduced evaporation from the surface in dry summers. Hummel et al. (1998) considered that "Soil conservation must be the compelling and overriding selling point" for no-till in Mediterranean countries. Bonari et al. (1995) working on clay soil at a hilly site near Pisa, Italy, found that annual runoff (averaged over two years) was 94 mm for ploughing and 57 mm for no-till. Corresponding results for soil loss were 28 and 3 t ha^{-1}. The reduced soil loss was accompanied by less loss of N attached to soil particles as ammonium or organic compounds. In Spain no-till has the ability to conserve water in low rainfall seasons and to protect the soil against erosion in wet seasons (Giráldez et al, 1997).

4.4. Losses of P

The eutrophication of water courses attributable to increased P loading is a serious environmental problem in Finland (Muukkonen et al., 2006). Risks of pollution from loss of particulate P during erosion can also be high on sloping ground in Sweden and Norway. High losses of particulate-bound P (PP) in runoff occur in Scandinavia from cultivated clay soils during warm, wet winters but losses of P can also occur as dissolved reactive P (DRP) which can account for 9-93% of the total P lost in runoff (Ulén et al., 2010). No-till can greatly reduce losses of PP but a stratified surface layer rich in P can develop in no-till soils from which an appreciably higher loss of DRP can occur than on ploughed soils. Puustinen et al. (2005) found that the loss of PP on no-till soil was 30% of that from ploughed soil (1.13 instead of 3.71 kg ha^{-1}) but DRP increased by 348% under no-till (2.02 instead of 0.58 kg ha^{-1}). Such very considerable increased losses of DRP in runoff after no-till compared to ploughing have also been attributed to the release of DRP from dead weeds following glyphosate application (Ulén et al., 2010) and to P leaching from fertilizers retained near the surface (Puustinen et al., 2005). Another explanation is that the increased organic C in the surface layers of no-till soils enhances the lability of the P already at high concentration from unincorporated fertilizer applications (Muukkonen et al., 2006). While the total loss of P will be lower after no-till than after ploughing, the loss of the dissolved reactive P fraction may be higher than after ploughing (Puustinen et al., 2005) raising doubts as to the relative value of no-till as a technique for reducing eutrophication of water courses. The risks of losses of PP and DRP in runoff need to be minimised by the maintenance of a high infiltration rate in no-till soils (Muukkonen et al. 2009) and increasing the internal drainage of the profile by tile drainage. The relative importance of P losses in the form of particulate P or as DRP will depend on the infiltration capacity and incidence of surface runoff (Alakukku et al., 2009a).

4.5 Losses of N

Losses of N can occur not only as nitrate leaching but also as nitrogen compounds attached to soil particles during runoff. Nitrate leaching is a serious problem in many parts of Europe and any crop/soil management practices which can reduce its extent, such as omitting autumn ploughing, will have particular importance (Hansen et al., 2010). There is a lack of consensus in the literature on the effect of no-till on nitrate leaching (Oorts et al., 2007c; Hansen et al., 2010). This variability appears to depend on soil type, the use of catch crops before spring-sown crops and the various pathways for water movement in structured

soils. Nevertheless, Tebrügge (2001) reported that a lack of soil loosening in autumn leads to less mineralization of nitrogen and reduced leaching of nitrate into ground water in some no-till soils with well-developed vertically orientated macroporosity through which excess rain water is conducted as bypass flow. This may be of major environmental importance in areas designated by the EU as Nitrogen Sensitive Areas.

Düring and Hummel (1995) reported lower nitrate concentrations in topsoil in autumn after no-till than after ploughing, but since greater downward drainage in no-till soils, especially in macro-pores, the amount of nitrate leached may be similar. The lack of consistent reductions in nitrate leaching for no-till compared to ploughing for autumn-sown crops on two sandy loam soils in Denmark (Hansen et al., 2010) was attributed to more rapid root growth on ploughed soil and thus a greater ability of crops to absorb nitrate before leaching could occur. Poor establishment of autumn-sown crops on no-till soil due to dry spells led to increased nitrate leaching compared to that on ploughed soil.

4.6. Greenhouse gas emissions

Soils are now recognised as having an important role in the emission of greenhouse gasses, studies on the influence of no-till have usually been restricted to only one gas and a limited range of soils. Results therefore tend to be tentative and to be highly dependent on local conditions and vary widely with changes in weather and crop management practices. Though rarely attempted, there is a need to study all three greenhouse gases (CO_2 , N_2O and $CH_{4)}$ simultaneously, as was undertaken by Regina and Alakukku (2010) over a 10-month period at 6 sites representative of typical soil types in Finland which had been under no-till for 5-7 years.

4.6.1. N_2O emissions

No-till influences the dynamics of soil nitrogen in several ways (Conen and Neftel, 2010). Factors influencing N_2O emissions from no-till include soil wetness and compaction status (which together influence soil aeration and the N_2O production mechanism through denitrification), soil temperature, nitrogen fertiliser type and application method, crop type and the extent of crop residues cover. Of these, soil moisture status is probably the most important (Ball et al., 2008; Rochette, 2008; Almaraz et al., 2009). The higher moisture content and reduced aeration under no-till, especially after rainfall on heavier poorly drained soils in northern Europe, leads to greater denitrification and emission of N_2O than under ploughing (Christian and Ball, 1994; Vinten et al., 2002; Oorts et al., 2007b; Ball et al., 2008; Regina and Alakukku, 2010), while very wet soils favour the reduction of N_2O to N_2. Highest N_2O fluxes typically occur at water-filled pore space in the range of 60-80%. The emissions of N_2O from 6 contrasting soils was strongly correlated with the total C and N contents of the 0-20 cm layer six contrasting soils in Finland (Regina and Alakukku (2010) which may explain higher N_2O fluxes from no-till soils. Six et al. (2004) observed increased N_2O emissions only during the first 10 years of no-till followed by a decrease after 20 years. This effect might be attributable to slow changes resulting in the improvement of internal structure and drainage of no-till soils. Increased N_2O formation in no-till soils may also be associated with higher numbers of earthworms since the gas is formed in their intestine (Regina and Alakukku, 2010).

On well-aerated soils the impact of no-till on N_2O emissions is small (Rochette, 2008) and some studies have indicated lower N_2O emissions with no-till than for ploughed soils

(Almaraz et al., 2009; Mutegi, 2010). The considerable level of variability is illustrated in Table 9. On a well-drained sandy loam soil in Denmark Mutegi et al. (2010) found that N_2O emissions from no-till were lower for no-till than for ploughing when residues are retained (as is usual), with no-till and ploughed soils showing N_2O emissions of 258 and 551 µg N m^{-2} day^{-1} respectively. This was attributed to complex interactions between the effects of residue-N transformation, C availability and soil physical conditions. Where legumes are incorporated by ploughing, N_2O emissions tend to be appreciably higher than with no-till, indicating a further advantage for no-till by including legumes in a rotation (Almaraz et al., 2009).

It is clear that further research is needed to establish the interacting role of several factors in addition to tillage, such as soil type, soil N status, soil aeration, soil temperature, crop type and residue management in influencing N_2O emissions and that a general conclusion about the influence of no-till is not possible.

4.6.2. CO_2 emissions from fuel use

. Fuel used in no-till operations is invariably less that than used with normal ploughing systems but the difference will depend strongly on the soil type, the depth of ploughing, the number and type of secondary cultivations. Tebrügge and Börhnsen (1997a) reported the average fuel consumption for growing small grains over a range of soils in Germany to be 43.55 l ha^{-1} for stubble cultivation, ploughing, secondary cultivation and sowing as compared to 6.8 l ha^{-} for no-till (sowing and plant protection), giving a potential saving of 37 l ha^{-1} equivalent to 84%. Other estimates of fuel saving with no-till compared to ploughing and secondary cultivations vary widely, for example: 50% (Khaledian et al., 2010), 68% (Koeller, 1989), 75-80% (Riley et al., 1994); 83% (Arvidsson, 2010b).

The effect of soil type on fuel savings with no-till is of importance. For a clay soil in Sweden fuel consumption for ploughing and cultivating and no-till treatments was 54 and 9 l ha^{-1}, respectively, while on a silty loam the corresponding values were 27 and 7 l ha^{-1} (Arvidsson (2010b), giving savings of 45 and 20 l ha^{-1} on the clay and silty loam soils respectively. Similarly in Germany fuel consumption for ploughing, cultivating and sowing were reported to be 44, 54 and 78 l ha^{-1} for sand, loam and clay soils in Germany (Koeller, 1989). The corresponding fuel usage for no-till and very shallow cultivation were 17, 20 and 25 l ha^{-1} giving savings with no-till of 27, 34 and 53 l ha^{-1}, respectively. The emission of CO_2 from the production and consumption of tractor fuel is approximately equal to 376 kg CO_2 per 100 l diesel (Tebrügge, 2001) Therefore, for a range of soil types, an average saving of 40 l ha^{-1} by using no-till in place of ploughing would achieve a reduced emission of 376 x 0.4 x 12/44 = 41 kg CO_2-C ha^{-1} for each crop season. Tebrügge, (2001) claims that no-till has the potential, if adopted on 40% of the EU land area (the proportion considered to be suitable without major problems), of reducing CO_2 emissions by 4.2 Mt y^{-1} as a result of lower fuel consumption alone.

4.6.3. *CO_2 emissions from soil*

CO_2 emissions from soil are attributable to a number of different processes which can be divided into short-term effects immediately after ploughing and longer-term effects during the main growing season. Ploughing tends to produce a marked short-term flux of CO_2 in the first few days after soil disturbance with longer-term differences between tillage treatments being minor (Vinten et al., 2002; Chatskikh and Olesen, 2007). Similarly López-Garrido et al. (2009) found, for conditions in south west Spain, that tillage caused a sharp increase in soil CO_2 emissions immediately after tillage. Throughout the year, cumulative losses of carbon

through CO_2 emissions were higher under conventional tillage than under no-till and reduced tillage. Álvaro-Fuentes et al. (2004, 2007ab, 2008) studied short- and long-term CO_2 fluxes in north east Spain. Soil CO_2 emissions just after tillage were 40% higher under conventional tillage than under no-till as the CO_2 accumulated in soil pores was released to the atmosphere after the tillage event. At the same time, tillage has an accumulative effect during the whole growing season in increasing microbial decomposition resulting in 20% higher soil CO_2 emissions under conventional tillage than under no-till. Part of this effect can be attributed to greater root respiration under ploughing, especially in warmer months (Almaraz et al., 2009). Reduction of CO_2 fluxes under reduced tillage compared with conventional tillage have also been reported by Sánchez et al. (2002, 2003) in soils of the Spanish plateau.

Under certain conditions, however, higher CO_2 emission rates have been observed after no-till than after ploughing (Almaraz et al., 2009). For instance over a 331-day period in Northern France CO_2 emissions from long-term no-till and ploughing were 4064 and 3160 kg CO_2-C ha^{-1} respectively (Oorts et al. 2007b). The greater emission under no-till was considered to be associated with decomposition of old weathered residues present at the surface as a result of the unusually warm weather during the monitoring period. Another example of increased CO_2 efflux under no-till (Table 8) was observed by Yamulki and Jarvis (2002), though they offered no explanation for the difference between tillage treatments. In Table 9 the periods of measurement are mostly quite short so that flux variation at different periods of the crop cycle may not be fully reported in contrast to the studies reported by Regina and Alakukku (2010) who measured CO_2 and N_2O fluxes during a 10-month period at approximately monthly intervals.

Table 8
Contributions of CO_2 (excluding in tractor fuel) and N_2O emissions (expressed as CO_2 equivalent) to net climate forcing budgets after no-till and ploughing in several countries (fluxes relate to the stated time periods).

Country	Aeration status	Time period	N_2O loss expressed as kg CO_2-C ha^{-1}		Change in CO_2 emission in no-till relative to ploughing (kg CO_2-C ha^{-1})	Overall CO_2 budget in no-till relative to ploughing (kg CO_2-C ha^{-1})	References
			No-till	Ploughed			
France	Good	11 months	168±66	102±19	+904	+970	Oorts et al. (2007b)
Denmark	Medium	3 months	127	263	-990	-1126	Chatskikh and Olesen (2007)
Scotland	Poor	200 days[1]	7070	2180	+93	+4980	Vinten et al. (2002)
England	Poor	20 days	1143	900	+700	+943	Yamulki and Jarvis (2002)

[1]Comprising 4 post-sowing periods over 3 years

Considerable variability of CO_2 emissions has been found in Finland where Regina and Alakukku (2010) report higher fluxes with no-till than with ploughing at 2 out of 6 sites while at one site the opposite effect was found and no differences were observed at 3 sites, with CO_2 emissions being strongly correlated with total C and N and mineral N. There are, therefore, no consistent effects of tillage on CO_2 emissions, these being related to water content, climate and the amount, type and stratification of organic matter. An understanding of these effects requires further research.

Differences in CO_2 emissions between tillage systems are likely to result from both short-term and long-term effects (Oorts et al., 2007b). Short-term effects are due to the physical disturbance of soil and crop residues. Long-term effects include the effects of changes in soil qualities over several years. Most studies concentrate on short-term effects. Long-term CO_2 emissions involve complex interactions between the different factors determining emissions (temperature, rainfall, water content, SOM, crop residues) (Oorts et al., 2007b).

4.6.4. CH_4

There is a lack of European data on methane emission or absorption by the soil. Ball et al. (1999) showed that methane oxidation was greater under no-till than under ploughing, but the oxidation rates were low and unlikely to contribute substantially to the greenhouse gas budget. In the USA, no-till has been shown to increase methane oxidation in comparison to minimum and conventional tillage (Ussiri et al., 2009). Other work has shown that no-tillage can emit methane and at a greater rate than from conventional tillage (Alluvione et al., 2009) but most studies suggest that tillage has a minor influence on the exchange of methane. Regina and Alakukku (2010) conclude that CH_4 fluxes were not affected by no-till but suggest that, depending on soil conditions, a weak CH_4 flux with no-till might be negative or positive.

4.7. Sequestration of carbon

The sequestration of carbon by soils represents an important component in the balance of carbon within the environment (Lal, 2007). Article 3.4 of the Kyoto Protocol refers to the desirability of promoting C sequestration by soils (Wereszczaka et al., 2009). It is therefore important to establish the effect of no-till on C sequestration and what factors may influence this.

Although there is no consistent effect of tillage on long-term CO_2 (Section 4.6.2.), early studies established that the SOC content of no-till soils, at a depth of 0-30 cm or less, frequently exceeded that after ploughing and did so almost invariably at 0-15 cm depth with a pronounced stratification of SOC with depth usually apparent within three years of commencing no-till (Yang et al., 2008).

A summary by Tebrügge (2001) of early long-term studies in Canada, Germany, Italy, Spain and Portugal indicated that no-till can be expected to show an additional accumulation compared to ploughing of 1100, 1500, 800, 800 and 1000 kg C ha^{-1} yr^{-1}, respectively. Data from long-term trials summarised by of sampling not given). Similarly in France, measurements made on the Boigneville long-term field trial (32 years) have shown that the difference between C stocks in ploughed and no-till treatments within the 0-28 cm depth during a 32-year period (1970-2002) was +5.2 Mg C ha^{-1} in favour of no-till (Oorts at al., 2007a) which is equivalent to 162 kg C ha^{-1} yr^{-1}. In a semi-arid area in northern central

Spain the soil carbon accumulation to a depth of 30 cm after 10 years of no-till was 25% higher than after mouldboard ploughing (Sombrero and De Benito, 2010).

A global assessment of 67 long-term experiments, involving 276 paired no-till and ploughed treatments (West and Post, 2002) indicated, at depths usually of 30 cm or less, a mean increase of 570 kg C ha^{-1} yr^{-1} for no-till compared with ploughing but with considerable variation as has been found in Europe (Table 9).

Table 9
Examples of average annual change in soil organic carbon (SOC) after no-till compared to ploughing in Europe (in ascending order of SOC change).

Country	Number expts.	Depth (cm)	Duration (y)	SOC change (kg C ha^{-1} y^{-1})	Reference
Scotland[1]	1	0-60	6	0	Sun et al. (2010)
Switzerland[2]	1	0-40	19	0	Anken et al., (2009)
Spain[3]	1	0-40	13	158	Hernánz et al. (2002)
France[4]	1	0-20	32	162	Oorts et al. (2007a)
Spain[5]	3	0-40	15-18	20-187	Álvaro-Fuentes et al. (2008)
England[6]	4	0-30	5 - 9	340	Bhogal et al. (2007)
Scotland[7]	1	0-20	23	510	Ball et al. (1994a)
Portugal[3]	1	0-30	4	750	Basch (2002)
Germany[8]	1	0-30	3	1000	Fleige and Baeumer (1974)
Spain[3]	1	0-30	11	1000	López-Fando and Pardo (2001)
Spain[9]	1	0-30	10	1300	Sombrero and De Benito (2009)

Soil types: [1]Dystric Fluvic Cambisol [2]Orthic Luvisol [3]Luvisol [4]Haplic Luvisol [5]Inceptisol, Calcisol [6]Orthic Acrisol, Gleyic Cambisol, Dystric Cambisol [7]Eutric Cambisol, Gleysol [8]Orthic Podsol [9]Typic Calcixerolls

In general these initial research results supported the hypothesis that higher SOC at 0-30 cm depth is a valid indication of greater C sequestration after no-till than after ploughing and led to confident predictions that no-till offered an important method to mitigate anthropogenic CO_2 emissions (Spargo, et al., 2008). For instance, Smith et al. (1998) estimated that 100% conversion to no-till farming in the EU would sequester, through fuel savings and soil organic matter increases, about 26 Mt C yr^{-1} or 4% of the total man-made carbon released annually as CO_2 in Europe.

Recent research has shown, however, that this hypothesis is not universally correct and may be invalid and that very wide differences can be expected according to climate, soil type, cropping system and duration of no-till and ploughed treatments and also that sampling to a depth of 40 cm, 60 cm or even 1 m (Lal, 2009), may be necessary to establish fully the role of no-till in C sequestration. Sampling at depths of 0-30 cm or less has resulted in over-estimation of soil C sequestration under no-till (Baker et al., 2007) since considerable accumulations of C have been found below 30 cm for ploughed soils which were absent at this depth after no-till (Snyder et al., 2009). Luo et al., (2010) showed that on 69 paired studies (mostly in North America) the adoption of no-till resulted in an increase of 3.15 t C ha^{-1} at 0-10 cm but declines of 2.40 t C ha^{-1} and 0.90 t C ha^{-1} at 20-30 cm and 30-40 cm respectively with no differences below 40 cm. No-till did not increase overall soil C except where double cropping per year was used. They suggest that ploughing will result in deeper root growth than in no-till. Pooling the results of surveys conducted in the USA, Canada and Brazil by Blanco-Canqui and Lal (2008) and Christopher et al. (2009) shows that the gain in C sequestration by no-till over ploughing varied from +4.94 Mg C ha^{-1} yr^{-1} to -11.0 Mg C ha^{-1} yr^{-1}. Both these extreme values, which exceed the limits yet reported within Europe, were found on silt loam soils within Pennsylvania.

Among the possible factors influencing the relative C sequestration under no-till and ploughing are soil factors, rainfall, temperature, crop characteristics (such as the amount and fate of crop residues applied and root distribution). Snyder et al. (2009) consider that no-till will show positive results only if crop productivity (i.e. biomass) with no-till is equal to or greater than that for ploughing which is not always the case. Higher C sequestration under no-till relative to ploughing will be encouraged by a proneness to erosion and drought on ploughed soils, good drainage, silt loam texture and good earthworm activity, while lower C sequestration after no-till can be expected on poorly drained soils with slow internal drainage, heavy textured soils with a proneness to smearing leading to poor germination, suboptimal soil temperatures in spring, and a proneness to compaction (Personal communication: R. Lal). Lack of differences in C sequestration after no-till and ploughing in Europe (Table 9) tend to be in cool, wet climates where the oxidation of incorporated crop residues proceeds only slowly, viz. Switzerland (Anken et al., 2009) and Scotland (Sun et al., 2010). Anken et al., (2004, 2009) compared SOC after 19 years of no-till and mouldboard ploughing at a cool, moist site (average annual rainfall 1183 mm) in north-eastern Switzerland. The total SOC within 0-40 cm depth was 65 Mg C ha^{-1} with no significant evidence that no-till was responsible for increased C sequestration. In dry climates the concentration of crop residues near the surface may stimulate their decomposition at a faster rate than if they had been incorporated at depth (Six et al., 2004).

The rate of any enhanced carbon storage under no-till has been found to peak at about 5 to 10 years with SOC reaching a new equilibrium in 15 to 20 years (West and Post, 2002). Bhogal et al. (2007) suggest that enhanced carbon storage potential with no-till will decline after about 20 years as a new equilibrium carbon content is reached.

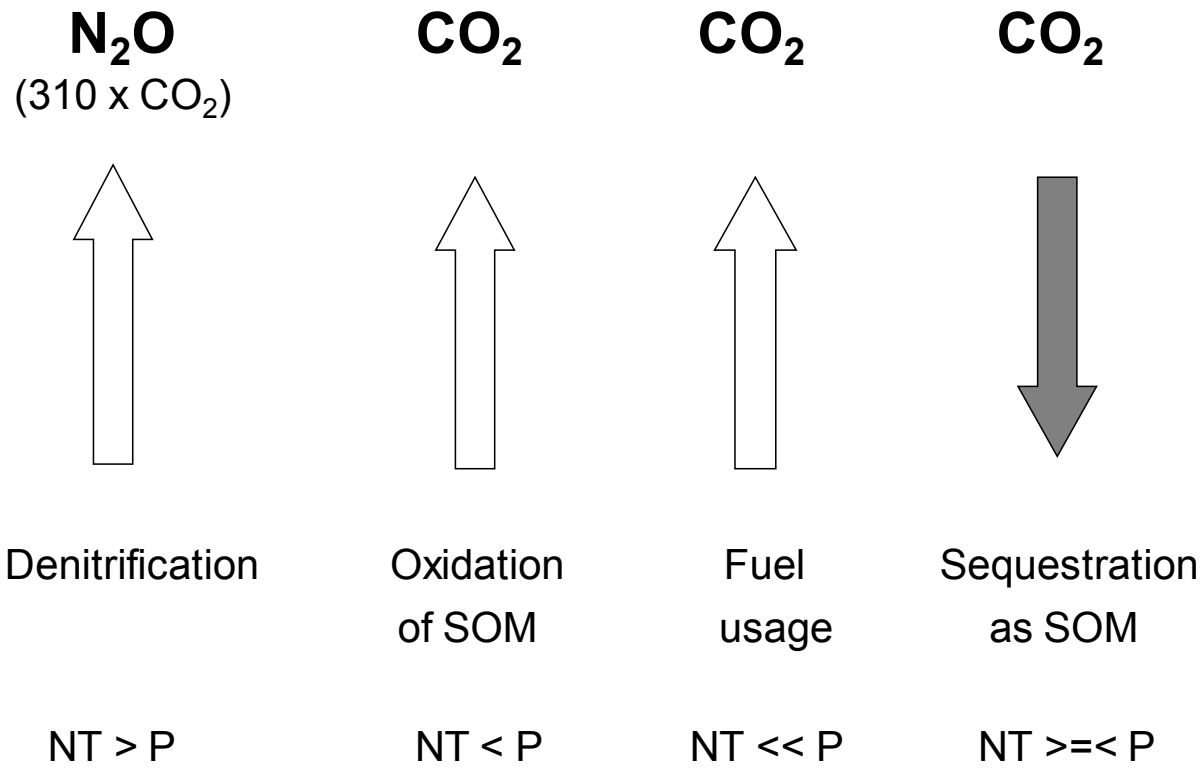
There is a need to take differences in bulk density within the profile into account when comparing SOC accumulation for different tillage treatments. Lee et al. (2009) made a comparison of several methods to correct total soil carbon data for tillage responses coupled to changes in bulk density and they suggested the use of an equivalent soil mass method.

The very wide, and not fully understood, variation in C sequestration after no-till compared to ploughing suggests that further research is needed over a range of soils, crops and climates before any general conclusions can be made. It should not be overlooked that stratified increases in C near the surface in no-till will have numerous benefits to soil quality, even if the overall increase of C within the no-till profile is small or non-existent.

4.8 Net effects of no-till and ploughing on net climate forcing

True mitigation of global warming potential (GWP) by no-till is only possible if any increased carbon sequestration effect exceeds the GWP attributable to the net upward fluxes of the three major biogenic greenhouse gases (i.e. CO_2, N_2O and CH_4) (Fig. 2.).

Fig. 2. Conceptual representation of generalised overall influence of no-till compared with ploughing on the components of net climate forcing (see text for discussion).



Several authors indicate that higher greenhouse gas emissions, N_2O in particular, from no-till may counterbalance greater C sequestration (Oorts et al., 2007b; Smith and Conen, 2004) with the effect being greatest on poorly drained, fine-textured agricultural soil (Rochette, 2008). Thus improved nitrogen management to reduce N_2O emissions is essential to realize

the full benefit of any increased C storage with no-till (Six et al., 2004), particularly on poorly aerated soils. The typical rate of C storage suggested by Bhogal et al (2007) for England and Wales is 310 (±180) kg C ha^{-1} y^{-1}. A nitrous oxide emission of only 1 kg N_2O ha^{-1} y^{-1} greater from no-till than from ploughing would balance this GWP. Further examples of the CO_2 (equivalent) components in the budget for net forcing effect after no-till and ploughing (excluding CO_2 emissions in tractor fuel) are shown in Table 8 and emphasise the importance of N_2O emissions in influencing the net forcing budgets of no-till. Snyder et al. (2009) concluded that there was no clear response – positive or negative – for the mitigation of greenhouse gas emissions using no-till compared to conventional tillage. In some regions where stored organic matter increases, the net GWP can decrease whereas in other areas the GWP can increase slightly when changing from conventional tillage to no-tillage. Further research is needed to improve confidence in predictions of the benefits of no-till in reducing the overall net climate forcing and differences in usage of tractor fuel, N fertiliser and herbicides must be included.Particular problems arise because data on gas emissions are subject to large short-term variation and are often presented for appreciably different periods in the crop season (Table 8).

5. Prospects for increased uptake of no-till in Europe

5.1. Influence of climate changes

Stability of acceptable yields under a range of seasonal weather conditions and anticipated changes in climate is of major importance to farmers. Changing climate in northern Europe is tending to result in milder winters, wetter soils in autumn and spring and longer growing seasons which are already influencing the choice of tillage systems. In south-east England average rainfall during establishment of winter-sown crops (August-October) has increased from 61 mm (1971-1980) to 74 mm (1991-2000) (Davies and Finney, 2002). This trend is forecast to continue. In southern and central Europe climate changes are expected to increase drought problems during hotter, drier summers with wetter, warmer winters. To maintain yields in areas of low rainfall an increasing emphasis is anticipated on minimal soil disturbance and maximum residue coverage to keep evaporation to a minimum (Birkás et al., 2008). If, as is expected, the winter climate in northern Europe becomes milder and wetter there will be enhanced risks of erosion, runoff and pollution of water courses from ploughed soils which might normally be frozen and snow covered, giving greater opportunities for no-till on well drained soils (Muukkonen et al., 2009).

5.2. Future crop and soil management policies

Environmental concerns related to greenhouse gas emissions and soil erosion may influence government policy regarding adoption of no-till in future. If no-till can reduce production costs while reducing global warming potential appreciably and meeting enhanced standards for environmental and food quality, it would have important advantages, even if yields were not higher, or even slightly lower, than following ploughing. Düring et al. (1998) consider that if the environmental advantages of no-till were considered to be sufficiently important then government subsidies could be awarded for the first three years of no-till when reduced yields may act as a deterrent to commercial adoption. To reduce erosion problems in Norway subsidies are paid to farmers who do not plough in autumn while in Denmark and southern Sweden subsidies are payable to promote spring ploughing to reduce N leaching (Ulén et al., 2010). However, recent research seems to contradict earlier suggestions that no-till would result in appreciable carbon sequestration and thus it may not

justify inclusion in trading credits for carbon within the concept of "farming carbon" (Lal, 2007).

Although no-till offers reduced emissions of CO_2 through reductions in use of fuel it seems that no-till will never be acceptable within the standards for organic or biodynamic farming owing to the dependence on herbicides. The difficulties of employing reduced tillage systems within organic management are discussed by Berner et al. (2008) and Peigné et al. (2007). Restricted use of herbicides in no-till systems may be enforced as a result of recent EU Directives concerned with water quality (Drinking Water Directive) and Water Framework Directive). For instance the widespread use of metazachlor for oilseed rape is now under review within the Water Framework Directive (Morris et al., 2010). The EU Agri-Environmental Programme may restrict the application of slurry or manure to no-till land unless it is injected or mixed with the topsoil.

The Soil Thematic Strategy was ratified by the European Commission on September 22, 2006. The strategy aims to address soil degradation throughout 27 EU Member States. The implementation of this as a Soil Directive could encourage the uptake of no-till as this farming practice addresses several of the identified soil threats (Commission of the European Communities, 2006). The Common Agricultural Policy (CAP), which controls government payments to farmers throughout the EU, is due for major reform in 2013 and it seems likely that environmental concerns will gain greater emphasis in influencing payments thereafter. Financial inducements are already available to encourage the uptake of conservation and no-till systems in Saxony and after a ten-year programme area these practices amounted to 27% of the total arable area (IRENA, undated). However, a low degree of acceptance of alternative tillage systems by Spanish farmers is attributed to inadequate extension and technology transfer systems and lack of access to suitable machinery and equipment (Cantero-Martínez and Gabiña, 2004; Angás et al., 2004).

5.3. Changes in production costs and crop prices

Increases in costs, particularly of fuel and machinery, may force farmers to give greater attention to abandoning mouldboard ploughing provided that no-till can achieve suitably high yields. Moves towards farm amalgamation and contracting out tillage operations, already widespread in Europe (Mikkola et al., 2005), will heighten demand for low cost, high capacity cropping systems which could be based on no-till. The machinery investment for ploughing systems exceeds that for no-till by a factor of 1.63, while maintenance costs are 4 times higher, fuel costs are 6.5 times higher and working time per unit area is 5 times higher and the combined performance costs are 4.2 times higher for ploughing than for no-till (Tebrügge, 2001). These differences are likely to become even more important in future if profit margins for crop production decline and labour and fuel costs rise.

Mineral fertilizers also contribute significantly to overall production costs. Especially on soils having depleted organic matter in southern Europe, increased levels of soil organic carbon near the surface as a result of adopting no-till could significantly reduce the need for mineral N inputs in cereal production. Carvalho et al. (2005) reported that the increase from 1 to 2% soil organic matter, obtained under long-term no-till conditions, could account for a reduction of 62 kg N ha^{-1} as fertiliser to achieve the optimum economic yield level.

Water and energy costs are becoming increasingly important for the economic viability of irrigated field crops in the southern European countries. The practice of no-till is frequently mentioned as a water-saving technique, due to increased infiltration, reduced evaporation and increased storage. US studies clearly indicate that no-till could contribute to water savings when compared to conventional tillage (Wagger and Cassel, 1993; Norwood, 2000).

In spite of all the apparent economic advantages of a move away from ploughing, Tebrügge (2001) finds it "difficult to understand farmer reluctance to accept no-till." However, although the area under no-till is still small, economic circumstances are increasingly favouring the uptake of no-till which is now actively promoted by the European Conservation Agriculture Federation (ECAF) and the Spanish Conservation Agriculture Association.

6. Conclusions

1. In northern and western Europe commercial uptake of no-till is currently very limited but has recently increased in Finland and other parts of Scandinavia. Initial hopes among certain research workers, often based on results of small plot experiments, in many northern regions of Europe for widespread commercial exploitation of no-till have proved to be unfounded, largely because of unanticipated problems with crop residues, seasonally variable yields and weed control. In general similar yields for winter-sown crops on well-drained soils have been obtained with no-till and ploughing but yields for spring-sown crops with no-till have often been somewhat lower. The interaction of factors related to soil properties, machinery usage, soil compaction, weather conditions, timeliness of sowing, weed control problems and crop residue handling have been found to be highly complex. Economic factors related to the production of winter- and spring-sown cereals are currently tending towards a more favourable basis for the adoption of no-till but a number of technical problems continue to restrict uptake in practice.

2. Throughout the wetter parts of northern Europe ploughing is still very widely adopted and is a particularly effective method of seedbed preparation on poorly drained soils because of its ability to provide surface drainage and aeration for the topsoil, especially in spring, to control weeds and to remediate surface compaction. The continued and widespread use of mouldboard ploughing or non-ploughing cultivations at reduced depth is anticipated in much of northern Europe unless economic incentives for no-till increase markedly.

3. In south western Europe the commercial uptake of no-till is now increasing as a result of perceived advantages in terms of soil and water conservation and reduced costs on larger farms. No-till has generally given equal or higher yields than after ploughing for winter-sown crops and savings in cost, especially on larger farms, may act as a powerful stimulus to its further adoption in those areas. In Mediterranean countries, no-till and the preservation of surface residues seem increasingly likely to become standard commercial practice because of better economics and improved soil and water conservation.

4. In all parts of Europe the commercial uptake of no-till depends closely on the successful handling of surface residues, weed control, compaction control and the correct selection and use of appropriate herbicides and direct drills. Controlled traffic farming and the use of rotations offer opportunities for enhanced commercial production with no-till. A high standard of managerial skills is essential, together with access to experienced advisors and consultants with up-to-date knowledge of all relevant environmental regulations and directives.

Environmental and economic factors may both favour the future adoption of no-till with financial support for no-till possibly becoming part of government environmental support policies.

5. Further quantification of all the environmental impacts of no-till is needed, particularly with respect to the influence on overall net climate forcing and pollution of water courses. The emission of greenhouse gases is extremely variable and the various factors involved, including fuel use, have not yet been fully evaluated for a wide range of crops, soils and climates. Carbon sequestration is not universally increased under no-till compared to ploughing and may vary widely with crop, soil and climate relations which are not yet fully established. Further research on the environmental aspects of the complete no-till system is needed.

6. Much early information on no-till in Europe was based on misleading results due to the use of short-term or monocultural experimentation, lacking full attention to economic implications. There is particular need for research into improved methods of non-herbicidal weed control in no-till systems using, for example, rotations and occasional shallow cultivations. Further research is also needed into the evaluation of the impact of no-till on grain quality (protein content, mycotoxins). No-till induces a dramatic change in the soil environment; this has consequences on the major plant nutrients (N, P, K) which still have to be better understood. The number of long-term no-till experiments (>5 years) in Europe over a range of soils, fertiliser applications and climate conditions with crops grown within rotations is still limited. Generalisation of conclusions from experiments of less than 3 years duration is unwise due to climatic variability and initial development of soil structural characteristics. The current economic and environmental potential of continuous no-till under rotational cropping has not been fully evaluated.

7. The success of no-tillage, both for crop production and for mitigating climate change is strongly related to soil wetness and susceptibility to compaction. Greater awareness and better interpretation of the spatial and time distribution of soil wetness and water deficits, as influenced by climate and soil type, will help improve the identification of soils and regions suitable for the successful uptake of no-till. A European-wide classification of the suitability of soils for no-till should be considered.

Acknowledgements

We are grateful for helpful comments received from Professor J.C. Holmes, Dr J.D. Pidgeon, and the three unknown referees which greatly contributed to improving the quality of the manuscript and to Professor Laura Alakukku for providing additional information on no-till research in Finland.

References

Alakukku, L., Uusitalo, R., Särkelä, A., Lahti, K., Valkama, P., Valpasvuo-Jaatinen, P., Ventela, A-M., 2009a. Phosphorus stratification in the Ap horizon of ploughed and no-till soils and its effect on P forms in surface runoff. Proceedings of 18th ISTRO Conf., Izmir, Turkey, Paper T6-004.

Alakukku, L., Ristolainen, A., Salo, T., 2009b. Grain yield and nutrient balance of spring cereals in different tillage systems. Proceedings of 18th ISTRO Conf., Izmir, Turkey, Paper T6-005, pp. 1-7.

Almaraz, J.J., Zhou, X., Mabood, F., Madramootoo, C., Rochette, P., Ma, B-L., Smith, D.L., 2009. Greenhouse gas fluxes associated with soybean production under two tillage systems in southwestern Quebec. Soil Tillage Res., 104, 134-139.

Alluvione, F., Halvorson, A.D., Del Grosso, S.J., 2009. Nitrogen, tillage and crop rotation effects on carbon dioxide and methane fluxes from irrigated cropping systems. J. Environ. Qual. 38, 2023-2033.

Álvaro-Fuentes, J., López, M.V., Gracia, R., Arrúe, J.L., 2004. Effect of tillage on short-term CO_2 emissions from a loam soil in semi-arid Aragón (NE Spain), Options Méditerranéennes, Serie A, 60, 51-54.

Álvaro-Fuentes, J., Cantero-Martínez, C., López, M.V., Arrúe, J.L., 2007a. Soil carbon dioxide fluxes following tillage in semiarid Mediterranean agroecosystems. Soil Tillage Res. 96, 331-341.

Álvaro-Fuentes, J., López, M.V., Arrúe, J.L., Cantero-Martínez, C., 2007b. Management effects on soil carbon dioxide fluxes under semiarid Mediterranean conditions, Soil Sci. Soc. Am. J. 72, 194-200.

Álvaro-Fuentes, J., López, M.V., Cantero-Martinez, C., Arrúe, J.L., 2008. Tillage effects on soil organic carbon fractions in Mediterranean dryland agroecosystems. Soil Sci. Soc. Am. J. 72, 541-547.

Angás, P., Cantero-Martínez, C., Karrou, M., Benbelkacem, A., Avci, M., 2004. Crop Production Technologies in Mediterranean Region. In: Cantero, C., Gabiña, D. (Eds.), Mediterranean Rainfed Agriculture: Strategies for Sustainability, Options Méditerranées, 60, 99-126.

Anken, T., Weisskopf, P., Zihlmann, U., Forrer, H., Jansa, J., Perhacova, K., 2004. Long-term tillage system effects under moist cool conditions in Switzerland. Soil Tillage Res. 78, 171-183.

Anken, T., Stamp, P., Richner, W., Walther, U., Weisskopf, P., Rek, J., 2006. Nitrate leaching and soil structural properties under conventionally cultivated and no-till crops. Proc. 17th Conf. ISTRO, Kiel, Germany, pp. 1535-1540.

Anken, T., Hermle, S., Leifelt, J., Weisskopf, P., 2009. The effects of tillage systems on soil organic carbon content under moist, cold-temperate conditions. Proceedings of 18th Int. Conf., Int. Soil Tillage Research Org., Izmir, Turkey, Paper T1-033, pp. 1-9.

Armand, R., Bockstaller, C., Auzat, A.-V., Van Dijk, P., 2009. Runoff generation related to intra-field soil surface characteristics variability. Application to conservation tillage context. Soil Tillage Res. 102, 27-37.

Arrouays, D., Balesdent, J., Germon, J.C., Jayet, P.A., Soussana, J.F., Stengel, P. (Eds), 2002. Stocker du carbone dans les sols agricoles de France? Contribution à la lutte contre l'effet de serre. Expertise collective INRA, Paris, France, 332 pp. (in French).

Arvidsson, J., 2010a. Direct drilling possible with a good preceding crop. Arvensis 4, 9-10 (Journal of the Swedish Rural Economy and Agricultural Societies, in Swedish).

Arvidsson, J., 2010b. Energy use efficiency in different tillage systems for winter wheat on a clay and silt loam in Sweden. Eur. J. Agron. 33, 250-256.

Baker, C.J., Saxton, K.E., Ritchie, W.R., 1996. No-tillage Seeding Science into Practice. CAB International, Wallingford, UK, 258 pp.

Baker, J.M., Ochsner, T.E., Venterea, R.T.,Griffis, T.J., 2007. Tillage and carbon sequestration – what do we really know? Agric. Ecosys. Envir. 118, 1-5.

Ball, B.C., 1986. Provisional land grouping for selection of cultivation requirement for winter barley in Scotland. Soil Tillage Res. 7, 7-18.

Ball, B.C., O'Sullivan. M.F., 1982. Soil strength and crop emergence in direct drilled and ploughed cereal seedbeds in seven field experiments. J. Soil Sci. 33, 609-622.

Ball, B.C., Davies, D.H.K., 1997. Weed and pest control in various systems in Scotland. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop III, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 9-16.

Ball, B.C., Lang, R.W., O'Sullivan, M.F., Franklin, M.F., 1989. Cultivation and nitrogen requirements for continuous winter barley on a Gleysol and a Cambisol. Soil Tillage Res. 13, 333-352.

Ball, B.C., Franklin, M.F., Holmes, J.C., Soane, B.D., 1994a. Lessons from a 26-year tillage experiment on cereals In: Proceedings 13th International Conference of the International Soil Tillage Research Organisation, Aalborg, Denmark, Vol. 2, pp. 757-762.

Ball, B.C., Lang. R.W., Robertson, E.A.G., Franklin, M.F., 1994b. Crop performance and soil conditions on imperfectly drained loam after 20 to 25 years of conventional tillage or direct drilling. Soil Tillage Res. 31, 97-118.

Ball, B. C., Tebrügge, F., Sartori, L., Giráldez, J.V., González, P., 1998. Influence of no-tillage on physical, chemical and biological soil properties. In: Tebrügge, F., Böhrnsen, A. (Eds.),

Experience with the Applicability of No-tillage Crop Production in the West-European Countries. Final Report., Fachverlag Köhler, 35396 Giessen, Germany, pp. 7-27.

Ball, B.C., Scott, A., Parker J.P., 1999. Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Tillage Res. 53, 29-39.

Ball, B.C., Crichton, I., Horgan, G. W., 2008. Dynamics of upward and downward N_2O and CO_2 fluxes in ploughed or no-tilled soils in relation top water-filled pore space, compaction and crop presence. Soil Tillage Res. 101, 20-36.

Barros, J.F.C., Basch, G. Carvalho, M., 2007. Effect of reduced doses of a post-emergence herbicide to control grass and broad-leaved weeds in no-till wheat under Mediterranean conditions. Crop Protection, 26, 1538-1545.

Barros, J.F.C., Basch, G. Carvalho, M., 2008. Effect of reduced doses of a post-emergence graminicide to control *Avena sterilis* L. and *Lolium rigidum* G. in no-till wheat under Mediterranean environment. Crop Protection, 27, 1031-1037.

Basch, G., 1988. Alternativen zum traditionellen Landnutzungssystem im Alentejo/Portugal, unter besonderer Berücksichtigung der Bodenbearbeitung. Göttinger Beiträge zur Land- und Forstwirtschaft in den Tropen und Subtropen, 31, 188 pp. (in German).

Basch, G., 2002. Mobilização do solo e ambiente. In: Basch, G. Teixeira, F. (Eds.), Mobilização de conservação do solo. APOSOLO, 7000 Évora, pp. 51-61 (in Portuguese).

Basch, G., 2005. Europe: The developing continent regarding conservation agriculture. Proceedings XIII Congreso de AAPRESID, El Futuro y los Cambios de Paradigmas, Rosario, Argentina, pp. 341-346.

Basch, G., Carvalho, M. 1994. Conditions and feasibility of no tillage in Portugal. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experience with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop I: Wissenschaftlicher Fachverlag, 35428 Langgöns, Germany, pp. 93-104.

Basch, G., Carvalho, M., 1997. Interactions between soil tillage and water logging. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop III, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 99-105

Basch, G., Teixeira, F. (Eds.), 2002. Mobilização de Conservação do Solo. APOSOLO, 7000 Évora, Portugal, 333 pp. (in Portuguese).

Basch, G., Carvalho, M., Düring, R.-A., Martins, R. 1995. Displacement of herbicides under different tillage systems. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experience with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop II:, Wissenschaftlicher Fachverlag, 35428 Langgöns, Germany, pp. 25-38.

Basch, G., Carvalho, M., Marques, F., 1997. Economical considerations on no-tillage crop production in Portugal. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experience with the applicability of no-tillage crop production in the West-European Countries. Proceedings of the EC-Workshop IV. Wissenschaftlicher Fachverlag, 35428 Langgöns, Germany, pp. 17-24.

Basch, G., Geraghty, J., Streit, B., Sturny, W.G., 2008. No-tillage in Europe – State of the Art: Constraints and Perspectives. In: Goddard, T., Zoebisch, M.A., Gan, Y., Ellis, W., Watson, A., Sombatpanit, S. (Eds.), No-Till Farming Systems Book. Special Publication No 3. World Association of Soil and Water Conservation, Thailand, pp. 159-168.

Bäumer, K., Köpke, U., 1989. Effects of nitrogen fertilization. In: Bäumer, K., Ehlers, W., (Eds.) Agriculture. Energy Saving by Reduced Soil Tillage. Commission of the European Communities, EUR 11258, pp.145-162.

Berner, A., Hildermann, I., Fliessbach, A, Pfiffer, L, Niggli, U., Mäder, P., 2008. Crop yield and soil fertility response to reduced tillage under organic management. Soil Tillage Res., 101, 89-96.

Bhogal, A., Chambers, B.J., Whitmore, A.P., Powlson, D.S., 2007. The Effect of Reduced Tillage Practices and Organic Matter Additions on the Carbon Content of Arable Soils. Scientific Report SP0561, Department of Environment, Food and Rural Affairs, London, UK, 47 pp.

Birkás, M., 2008. Environmentally-sound Adaptable Tillage. Akadémiai Kiadó, Budapest, Hungary, 354 pp.

Blanco-Canqui, H., Lal, R., 2008. No-tillage and soil-profile carbon sequestration : An on-farm assessment. Soil Sci. Sci. Am. J. 72, 693-701.

Boguzas, V., Kairyte, D., Jodaugiene, D., Lukosiunas, K., 2006. Effect of reduced and no-tillage, straw and green manure management on soil physical properties and earthworms. Proc. 17th Conf. ISTRO, Kiel, Germany, pp. 1566-1577.

Böhrnsen, A, 1995. Influence of straw management by no-tillage winter rape and winter wheat production. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop II, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 131-142.

Bonari, E., Mazzonzini, M., Peruzzi, A., Ginanni, M., 1995. Soil erosion and nitrogen loss as affected by different tillage systems used for durum wheat cultivated in a hilly clayey soil. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop II, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 81-91.

Borin, M., Sartori, L., Guipponi, C., Mazzoncini, M., Düring, R.-A., Basch. G. (Eds.), 1997. Effects of tillage systems on herbicide dissipation – an experimental approach at field scale. Unipress, Padova, 247 pp.

Børresen, T., 1999. The effect of straw management and reduced tillage on soil properties and crop yields of spring-sown cereals on two loam soils in Norway. Soil Tillage Res, 51, 91-102.

Bottinelli, N., Hallaire, V., Menasseri-Aubry, S., Le Guillou, C., Cluzeau, D., 2010. Abundance and stability of belowground earthworm casts influenced by tillage intensity and depth. Soil Tillage Res. 106, 263-267.

Bräutigam, V., Tebrügge, F., 1997. Influence of long-termed no-tillage on soil borne plant pathogens and on weeds. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop III, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 17-29.

Brito, I., de Carvalho, M., van Tuinen, D., Goss, M., 2006. Effects of soil management on the arbuscular mycorrhizal fungi in fall-sown crops in Mediterranean climates. Proc. 17th Conf. ISTRO, Kiel, Germany, pp. 622-628.

Calado, J.M.G., Basch, G. Carvalho, M., 2010. Weed management in no-till winter wheat *(Triticum aestivum* L.). Crop Protection 29, 1-6.

Campbell, D.J., Dickson, J.W., Ball, B.C., Hunter, R., 1986. Controlled traffic after ploughing or direct drilling under winter barley in Scotland 1980-1984. Soil Tillage Res. 8, 3-28.

Cannell, R.Q., 1985. Reduced tillage in north-west Europe - A review. Soil Tillage Res. 5, 129-177.

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 on Agriculture 9, 306-316.

Cannell, R.Q., Christian, D.G., Henderson, F.K.G., 1986. A study of mole drainage with simplified cultivations for autumn-sown crops on a clay soil. IV. A comparison of direct drilling and mouldboard ploughing on drained and undrained land on root and shoot growth, nutrient uptake and yield. Soil Tillage Res. 7, 251-272.

Cantero-Martínez, C., Vilardosa, J.M., 1993. Effect of different tillage systems in fallow and continuous crop of barley on soil water content in Mediterranean conditions. Proc. 3rd Wye International Conference on Sustainable Agriculture: Soil Management in Sustainable Agriculture. Wye, England, August-September 1993, pp. 484-487.

Cantero-Martínez, C., Gabiña, D., 2004. Evaluation of agricultural practices to improve efficiency and environment conservation in Mediterranean arid and semi-arid production systems. MEDRATE project, In: Cantero, C., Gabiña, D. (Eds.), Mediterranean Rainfed Agriculture: Strategies for Sustainability, Options Méditerranéennes, 60, pp. 21-34.

Cantero-Martínez, C., Lampurlanés, J., Vilardosa, J.M., 1994. Effect of three different tillage systems on water use and root development of barley in a semiarid environment. Proc. 3rd European Society for Agronomy. Italy, 18-22 September 1994, pp. 660-661.

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 Tillage Res. 105, 209-216.

Carvalho, M., Basch, G. 1994. Experiences with direct drilling in Portugal. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experience with the applicability of no-tillage crop production in the West-European Countries. Proceedings of the EC-Workshop I, Wissenschaftlicher Fachverlag, 35428 Langgöns, Germany, pp. 105-110.

Carvalho, M., Basch, G. 1995. Long term effects of two different soil tillage treatments on a Vertisol in Alentejo region of Portugal. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experience with the applicability of no-tillage crop production in the West-European Countries. Proceedings of the EC-Workshop II, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 17-23.

Carvalho, M., Basch, G., Alpendre, P., Brandão, M., Santos, F., Figo, M., 2005. A adubação azotada do trigo de sequeiro: o problema da sua eficiência. Melhoramento 40, 5-37 (in Portuguese).

Cedell, T., 1988. Direktsådd av oljeväxter. (Direct drilling of oilseed rape). Forskningsrapporter från oljeväxtodlarna IV 1987. Stiftelsen Svensk Oljeväxtforskning, pp. 11-20 (in Swedish).

Cerdà, A., Flanagan, D.C., le Bissonnais, Y., Boardman, J., 2009. Soil erosion and agriculture (Editorial). Soil Tillage Res., 106, 107-108.

Chamen, T., Alakukku, L., Pires, S., Sommer, C., Spoor, G., Tijink, F., Weisskopf, P., 2003. Prevention strategies for traffic-induced subsoil compaction: a review Part 2. Equipment and field practices. Soil Tillage Res. 73, 161-174

Chatskikh, D., Olesen, J.E., 2007. Soil tillage enhanced CO_2 and N_2O emissions from loamy sand soil under spring barley. Soil Tillage Res. 97, 5-18.

Christian, D.G., Ball, B.C., 1994. Reduced cultivations and direct drilling for cereals in Great Britain. In: Carter, M.R. (Ed.), Conservation Tillage in Temperate Agroecosystems. Lewis Publishers, Boca Raton, Florida, USA, pp. 117-140.

Christian, D.G., Bacon, E.T.G., 1995. Straw incorporation by different tillage systems on heavy clay soils in southern England. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop II, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 101-110.

Christian, D.G., Carreck, N.L., 1997. Strategies to control volunteer cereals in cereal rotations. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop III, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 31-42.

Christopher, S.F., Lal, R., Mishra, U., 2009. Regional study of no-till effects on carbon sequestration in midwestern United States. Soil Sci. Soc. Am. J. 73, 207-216.

Commission of the European Communities, 2006. Proposal for a Directive of the European Parliament and of the Council establishing a framework for the protection of soil and amending Directive 2004/35/EC Com (2006) 232 Final.

Conen, F., Neftel, A., 2010. Nitrous oxide emissions from land-use and land-management change. In: Smith, K. (Ed.), Nitrous Oxide and Climate Change. Earthscan, London, UK, pp. 143-161.

Cox, L., Calderón, M.J., Celis, R., Hermosín, M.C., Moreno, F., Cornejo, J., 1996. Mobility of metamitron in soils under conventional and reduced tillage. Fresen. Envir. Bull. 5, 528-533.

Cox, L., Calderón, M.J., Hermosín, M.C., Cornejo, J., 1999. Leaching of clopyralid and metamitron under conventional and reduced tillage systems. J. Environ. Qual. 28, 605-610.

Crochet, F., Nicoletti, J.P., Bousquet, N., 2008. Simplification du travail du sol: un intérêt économique variable d'une exploitation à l'autre. Perspective Agricoles, No. 344, Avril 2008, pp. 22-25 (in French).

Cuevas, M.V., Calderón, M.J., Fernández, J.E., Hermosín, M.C., Moreno, F., Cornejo, J., 2001. Assessing herbicide leaching from field measurements and laboratory experiments. Acta Agrophys. 57, 15-25.

Davies, D.B., Finney, J.B., 2002. Reduced Cultivations for Cereals: Research, Development and Advisory Needs under Changing Economic Circumstances. Home-Grown Cereals Authority, London, UK, Research Review 48, 57 pp.

Derpsch, R., 1998. Historical review of no-tillage cultivation of crops. In: Proc. 1st JIRCAS Seminar on Soybean research. No-tillage Cultivation and Future Research Needs, March 5-6, 1998, Iguassa Falls, Brazil, JIRCAS Working Report 3, pp. 1-18.

Derpsch, R., Moriya, K., 1998. Implications of no-tillage versus soil preparation on sustainability of agricultural production. In: Sustainable Land Use – Furthering Cooperation between People and Institutions, Advances in Geoecology 31, Vol II, Catena Verlag, Reiskirchen, Germany, pp. 1179-1186.

Derpsch, R., Friedrich, T., 2009. Development and current status of no-till adoption in the world. Proceedings of 18th Int. Conf., Int. Soil Tillage Research Org., Izmir, Turkey, Paper T1-041, pp. 1-16.

Düring, R.-A., Hummel, H.E., 1995. Leaching and decomposition of agrochemicals in no-tilled soils. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop II, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 39-48.

Düring, R.-A., Hummel, H.E., 1997. Glyphosate: Importance in no-till agriculture with regard to environmental side-effects. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop III, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 69-78.

Düring, R.-A., Basch, G., Hummel, H.E., 1998. Environmental aspects of no-tillage application - Erosion and leaching of agrochemicals. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experience with the Applicability of No-tillage Crop Production in the West-European Countries. Final Report., Fachverlag Köhler, 35396 Giessen, Germany, pp. 45-61.

Ehlers, W., 1997. Optimizing the components of the soil water balance by reduced and no-tillage. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop III, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 107-118.

Ehlers, W., Claupein, W., 1994. Approaches toward conservation tillage in Germany. In: Carter, M.R. (Ed.), Conservation Tillage in Temperate Agroecosystems. Lewis Publishers, Boca Raton, Florida, USA, pp. 141-165.

Ekeberg, E., Riley, H.C.F., 1997. Tillage intensity effects on soil properties and crop yields in a long-term trial on morainic loam soil in southeast Norway. Soil Tillage Res. 42, 277-293.

Errouisi, F., Moussa-Machraoui, S.B., Ben-Hammouda, M., Nouira, S., 2011. Soil invertebrates in durum wheat (Triticale durum L.) cropping system under Mediterranean semi arid conditions: A comparison between conventional and no-tillage management. Soil Tillage Res. 112, 122-132.

Fernández-Quintanilla C., 1997. Historia y evolución de los sistemas de laboreo. El laboreo de conservación. In: García Torres L., González Fernández P. (Eds.), Agricultura de Conservación. Fundamentos Agronómicos, Medioambientales y Económicos. Asociación Española de Laboreo de Conservación, Córdoba, Spain, pp. 1-12 (in Spanish).

Fernádez-Ugalde, O., Virto, I., Bescansa, P., Imaz, M.J., Enrique, A., Karlen, D.L., 2009a. No-tillage improvement of soil physical quality in calcareous, degradation-prone, semiarid soils. Soil Tillage Res. 106, 29-35.

Fernández-Ugalde, O., Virto, I., Imaz, M.J. Enrique, A., Bescansa, P., 2009b. Soil water retention characteristics and the effect on barley production under no-tillage in semi-arid conditions of the Ebro Valley (Spain). Proceedings of 18th ISTRO Conf., Izmir, Turkey, Paper T1-008.

Fleige, H., Baeumer, K., 1974. Effect of zero-tillage on organic carbon and total nitrogen content, and their distribution in different N-fractions in loessial soils. Agro-Ecosystems 1, 19-29.

Frankinet, M., Roisin, C., 1989. Regional experiences with reduced tillage in Belgium. In: Bäumer, K., Ehlers, W., (Eds.) Agriculture. Energy Saving by Reduced Soil Tillage. Commission of the European Communities, EUR 11258, pp.55-65.

Franzluebbers, A.J., 2002. Soil organic matter as an indication of soil quality. Soil Tillage Res. 66, 95-106.

Gerard, B.M., Hay, R.K.M., 1979. The effect on earthworms of plouging, tined cultivation, direct drilling and nitrogen in a barley monoculture system. J. Agric. Sci., Cambridge 93, 147-155.

Giráldez, J.V., Fereres, E., Gracía, M., Gil, J., González, P., Agüera, J., 1985. II Jornadas Técnicas sobre cereales de Invierno. Pamplona, Spain, Vol. 1, pp. 77-92 (in Spanish).

Giráldez, J.V., González, P. Ordóñez, R., Laguna, A., de Haro, J.M., 1997. Conservation tillage under extreme meteorological conditions in Southern Spain. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop III, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 119-125.

González, P., Giráldez, J.V., Ordóñez, R., Laguna, A., de Haro, J.M. 1997. No tillage crop production in Spain. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop IV, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 155-165.

Greener, M., Larsbo, M., Jarvis, N.J., 2007. Soil tillage effects on surface water pesticide concentrations. In: Re, A.A.M. del, Capri, E., Fragoulis, G., Trevisan, M., (Eds.) Environmental Fate and Ecological Effects of Pesticides. La Goliardica Pavese, Pavia, Italy, pp. 393-400.

Hansen, E., Munkholm, L.J., Melander, B., Olesen, J.E. 2010. Can non-inversion tillage and straw retainment reduce N leaching in cereal-based crop rotations? Soil Tillage Res. 109, 1-8.

Hay, R.K.M., Holmes, J.C., Hunter, E.A., 1978. The effects of tillage, direct drilling and nitrogen fertiliser on soil temperature under a barley crop. J. Soil Sci. 29, 174-183.

Hernánz, J.L., Sánchez-Girón, V., 1981. El No-laboreo: Resultados de una experiencia realizada en España. España Agrícola, 45, 37-51 (in Spanish).

Hernánz, J.L., Sánchez-Girón, V., 1994. 13 años de ensayos en "El Encín": Resultados a largo plazo. En "Conservar el suelo". Monsanto España SA., Madrid, Spain, pp. 16-17 (in Spanish).

Hernánz J.L., López R., Navarrete L., Sánchez-Girón V., 2002. Long-term effects of tillage systems and rotations on soil structural stability and organic carbon stratification in semi-arid central Spain. Soil Tillage Res. 66, 129-141.

Holmes, J.C., 1976. Effects of tillage, direct drilling and nitrogen in a long term barley monoculture system. Edinburgh School of Agric. Rep. 1976, pp. 104-112.

Hummel, H.E., Düring, R-A., Tebrügge, F., 1998. Future needs. In: Tebrügge, F., Böhrnsen A. (Eds.), Experience with the Applicability of No-tillage Crop Production in the West-European Countries. Final Report. Fachverlag Köhler, 35396 Giessen, Germany, pp. 79-89.

Imaz, M.J., Virto, I., Bescansa, P., Enrique, A., Fernandez-Ugalde, O., Karlen, D.L., 2010. Soil quality indicator response to tillage and residue management on semi-arid Mediterranean cropland. Soil Tillage Res. 107, 17-25.

IRENA, (undated). Indicator Fact Sheet. 14.2 Tillage systems. http://epp.eurostat.ec.europa.eu/portal/page/portal/agri_environmental_indicators/documents/IRENA%20IFS%2014%20-%20Farm%20management%20practices_FINAL.pdf. pp. 14

Javůrek, M., Vach, M., 2009. Impacts of long-term reduced tillage use on soil carbon content and water stable aggregates in Ortic Luvisol, loam soil. Proceedings of 18th ISTRO Conf., Izmir, Turkey, Paper T1-021.

Javůrek, M., Mikanova, O., Vach, M., 2006. Changes of biological actiovity in soil after 10 years of minimum and no soil tillage for stand establishment. Proc. 17th Conf. ISTRO, Kiel, Germany, pp. 1141-1147.

Jordan, V.W.L., Hutcheon, J.A., Kendall, D.A., 1997. Influence of cultivation practices on arable crop pests, diseases and weeds and their control requirements. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop III, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 43-50.

Känkänen, H., Alakukku, L., Salo, Y., Pitkänen, T., 2011. Growth and yield of different spring cereal species in zero tillage, compared to conventional tillage. Eur. J. Agron. 34, 35-45.

Khaledian, M.R., Mailhol, J.C., Ruelle, P., Mubarak, I., Perret, S., 2010. The inpacts of direct seeding into mulch on the energy balance of crop production system in the SE of France. Soil Tillage Res. 106, 218-226.

Kladivko, E.J., 2001. Tillage systems and soil ecology. Soil Tillage Res. 61, 61-76.

Koch, H-J., Heuer, H., Tomanová, O., Märländer, B., 2008. Cumulative effect of annually repeated passes of heavy agricultural machinery on soil structural properties and sugar beet yield under two tillage systems. Soil Tillage Res. 101, 69-77.

Koeller, K., 1989. Machinery requirements and possible energy savings by reduced tillage. In: Bäumer, K., Ehlers, W., (Eds.) Agriculture. Energy Saving by Reduced Soil Tillage. Commission of the European Communities, EUR 11258, pp. 7-16

Lacasta Dutoit, C., Meco Murillo, R., Maire, N., 2005. Evolución de las producciones y de los parâmetros químicos y bioquímicos del suelo, en un agrosistema de cereales, sometidos a diferentes manejos de suelo durante 21 años. Proceedings of "Congreso Internacional sobre Agricultura de Conservación - El Reto de la Agricultura, el Medio Ambiente, la Energia y la Nueva Politica Agraria Común", Córdoba, Spain, pp. 429-436 (in Spanish).

Lal, R., 2001. Thematic evolution of ISTRO: transition in scientific issues and research focus from 1955 to 2000. Soil Tillage Res. 61, 3-12.

Lal, R., 2007. Farming carbon. Soil Tillage Res. 96, 1-5.

Lal, R., 2009. The plow and agricultural sustainability. J. Sustainable Agric. 33, 66-84.

Lampurlanés. J., Cantero-Martínez, C., 2006. Hydraulic conductivity, residue cover, and soil surface roughness under tillage systems in semi-arid conditions. Soil Tillage Res. 85, 13-26.

Lee, J., Hopmans, J.W., Rolston, D.E., Baer, S.G., Six, J., 2009. Determining soil carbon stock changes: simple bulk density corrections fail. Agric., Ecosys. Env. 134, 251-256.

Linke, C. 1996. Direktsaat - Eine Bestandesaufnahme unter besonderer Berücksichtigung technischer, agronomischer und ökonomischer Aspekte. PhD Dissertation, Uni. Hohenheim, Germany, 482 pp. (in Grerman).

Lipiec, J., Kuś, J., Słowińska-Jurkirwicz, A., Nosalewicz, A., 2006. Soil porosity and water infiltration as influenced by tillage methods. Soil Tillage Res. 89, 210-220.

López, M.V., Arrúe, J.L., 1994. Soil and plant response to conservation tillage in rainfed barley production systems of Aragón, NE Spain. Proc. 3rd European Society for Agronomy. Italy, 18-22 September 1994, pp. 718-719.

López-Fando, C., Pardo, M.T., 2001. The impact of tillage systems and crop rotations on carbon sequestration in a Calcic Luvisol of Central Spain. In: Garcia-Torres, L., Benites, J., Martĩnez-Vilela, A. (Eds.), Conservation Agriculture – A Worldwide Challenge. World Congress on Conservation Agriculture, Vol. 2, pp. 135-139.

López-Garrido, R., Díaz-Espejo, A., Madejón, E., Murillo, J.M., Moreno, F., 2009. Carbon losses by tillage under semi-arid mediterranean rainfed agriculture (SW Spain). Span. J. Agric. Res. 7, 706-716.

Lötjönen, T., Isolahti, M., 2010. Direct drilling of cereals after ley and slurry spreading. Acta Agriculturae Scandinavica, Section B, Soil and Plant Sci. 60, 307-319.

Luo, Z., Wang, E., Sun, O.J., 2010. Can no-tillage stimulate carbon sequestration in agricultural soils? A meta-analysis of paired experiments. Agric. Ecosys. Environ. 139, 224-231.

Madejón, E., Murillo, J.M., Moreno, F., López, M.V., Arrúe, J.L., Álvaro-Fuentes, J., Cantero-Martínez, C., 2009. Effect of long-term conservation tillage on soil biochemical properties in Mediterranean Spanish areas. Soil Tillage Res., 105, 55-62.

Massé, J., Boisgontier, D., Bodet, J.M., Gillet, J.P., 1994. Feasibility of minimum tillage practices for annual cropping systems in France. In: Carter, M. R. (Ed.), Conservation Tillage in Temperate Agroecosystems. Lewis Publishers, Boca Raton, Florida, USA, pp. 167-179.

Melander, B., 1998. A review of the major experiences with weeds in non-inversion tillage systems within the European Community (EEC). In: Tebrügge, F., Böhrnsen A. (Eds.), Experience with the Applicability of No-tillage Crop Production in the West-European Countries. Final Report. Fachverlag Köhler, 35396 Giessen, Germany, pp. 63-68.

Melero, S., López-Garrido, R., Madejón, E., Murillo, J.M., Vanderlinden, K., Ordoñez, R., Moreno, F., 2009. Long-term effects of conservation tillage on organic fractions in two soils of southwest Spain. Agriculture, Ecosystems Environment, 133, 68-74.

Mikkola, H.J., Alakukku, L., Känkänen, H., Jalli, H., Lindroos, M.,
Huusela-Veistola, E., Nuutinen, V., Lätti, M., Puustinen, M., Turtola, E., Myllys, M., Regina, K., 2005. Direct drilling in Finland, a review. Proc. 4th Intern. Scientific and Practical

Conference, Ecology and Agricultural Machinery, May 25-26, 2005, St Petersburg, Vol. 2, pp. 141-151.

Montanarella, L., 2006. European Soil Protection Strategies. Proc. 17th Conf. ISTRO, Kiel, Germany, pp. 1586-1597.

Morris, N.L., Miller, P.C.H., Orson, J.H., 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 Tillage Res. 108, 1-15.

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 Tillage Res. 71, 163-173.

Munkholm, L.J., Hansen, E.M., Olesen, J.E., Melander, B., 2006. Minimum tillage demand for Danish sandy loams. Proc. 17th Conf. ISTRO, Kiel, Germany, pp. 443-449.

Mutegi, J.K., Lars, J., Munkholm, J., Petersen, B.M., Hansen, E.M., Petersen, S.O., 2010. Nitrous oxide emissions and controls as influenced by tillage and crop residue management strategy. Soil Biology Biochemistry 42, 1701-1711.

Muukkonen, P., Hartikainen, H., Lahti, K., Särkela, A., Alakukku, L., 2006. Effect of no-tillage and ploughing on the risk of phosphorus load from clay soils. Proc. 17th Conf. ISTRO, Kiel, Germany, pp. 932-937.

Muukkonen, P., Hartikainen, H., Alakukku, L., 2009. Effect of soil structure disturbance on erosion and phosphorus losses from a Finnish clay soil. Soil Tillage Res. 103, 84-91.

Norwood, C.A., 2000. Water use and yield of limited-irrigated and dryland corn. Soil Science Society of America Journal 64, 365-370.

Oorts, K., Bossuyt, H., Labreuche, J., Merckx, R., Nicolardot, B., 2007a. Carbon and nitrogen stocks in relation to organic matter fractions, aggregation and pore size distribution in no-tillage and conventional tillage in northern France. Eur. J. Soil Sci. 58, 248-259.

Oorts, K., Merckx, R., Gréhan, E., Labreuche, J., Nicolardot, B., 2007b. Determinants of annual fluxes of CO_2 and N_2O in long-term no-tillage and conventional tillage systems in northern France. Soil Tillage Res. 95, 133-148.

Oorts, K., Laurant, F., Mary, B., Thiebeau, P., Labreuche, J., Nicolardot, B., 2007c. Experimental and simulated soil mineral N dynamics for long-term tillage systems in northern France. Soil Tillage Res. 94, 441-456.

Peigné, J., Ball, B.C., Roger-Estrade, J., David, C., 2007. Is conservation tillage suitable for organic farming. Soil Use Manage. 23, 129-144.

Peigné, J., Cannavaciuolo, M., Gautronneau, Y., Aveline, A., Giteau, J.L. Cluzeau, D., 2009. Earthworm populations under different tillage systems in organic farming. Soil Tillage Res., 104, 207-214.

Pelegrín, F., Moreno, F., Martín-Aranda, J., Camps, M., 1990. The influence of tillage methods on soil physical properties and water balance for a typical crop rotation in SW Spain. Soil Tillage Res. 16, 345-358.

Pelosi, C., Bertrand, M., Roger-Estrade, J., 2009. Earthworm community in conventional, organic and direct seeding with living mulch cropping systems. Agron. Sust. Dev. 29, 287–295.

Puustinen, M., Koskiaho, J. Peltonen, K., 2005. Influence of cultivation methods on suspended solids and phosphorus concentrations in surface runoff on clayey sloped fields in boreal climate. Agric. Ecosys. Environ. 105, 565-579.

Rasmussen, K.J., 1988. Pløjning, direkte såning og reduceret jordbearbetning till korn. (Ploughing, direct drilling and reduced tillage for cereals). Tidsskr. Planteavl 92, 233-248 (in Danish with English summary).

Rasmussen, K.J., 1994. Experiments with no-inversion tillage systems in Scandinavia - Impacts on crop yields, soil structure and fertilization. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experience with the applicability of no-tillage crop production in the West-European Countries. Proceedings of the EC-Workshop I. Wissenschaftlicher Fachverlag, 35428 Langgöns, Germany, pp. 39-48.

Rasmussen, K.J., 1995. Straw management in various tillage systems in Denmark. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experience with the applicability of no-tillage crop production in the West-European Countries. Proceedings of the EC-Workshop II. Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 111-121.

Réal, B., Dutertre, A., Eschenbrenner, G., Bonnifet, J.P., Muller, J.M., 2004. Transfer de produits phytosanitaires par drainage, ruissellement ou percolation. Résultats de 10 campagnes d'expérimenation. XIXème conference du COLUMA, Dijon, France, 8-10 décembre 2004, pp. 70-75 (in French).

Regina, K., Alakukku, L., 2010 Greenhouse gas fluxes in varying soils types under conventional and no-tillage practices. Soil Tillage Res. 109, 144-152.

Riley, H., Børrensen, T., Ekeberg, E., Rydberg, T., 1994. Trends in reduced tillage research and practice in Scandinavia. In: Carter, M.R. (Ed.), Conservation Tillage in Temperate Agroecosystems. Lewis Publishers, Boca Raton, Florida, USA, pp. 23-45.

Rochette, P., 2008. No-till only increases N_2O emissions on poorly-aerated soils. Soil Tillage Res. 101, 97-100.

Rochette, P., Angers, D.A., Chantigny, M.H., MacDonald, J.D. 2009. Ammonia volatilization following surface application of urea to tilled and no-till soils: A laboratory comparison. Soil Tillage Res. 103, 310-315.

Rydberg, T., 2010. Direct drilling. In : Arvidsson, J. (Ed.), Research in Soil Tillage in 2009. Division of Soil Management, Swedish University of Agricultural Sciences, Uppsala, Sweden, Rep. 116, pp. 12-13 (in Swedish, with English summary).

Sánchez, M.L., Ozores, M.I., Colle, R., López, M.J., De Torre, B., García, M.A., Pérez, I., 2002. Soil CO_2 fluxes in cereal land use of the Spanish plateau : influence of conventional and reduced tillage practices. Chemosphere, 47, 837-844.

Sánchez, M.L., Ozores, M.I., López, M.J., Colle, R., De Torre, B., García, M.A., Pérez, I., 2003. Soil CO_2 fluxes beneath barley on the central Spanish plateau. Agric. For. Meteorol. 118, 85-95.

Schjønning, P., Høy, J.J., Munkholm, L.J., 2010a. Soil tillage effects on the development of winter wheat yields in Denmark. In: Petersen. J., Haarstrup, M., Knudsen, L., Olesen, J.E., (Eds.), Causes of Yield Stagnation in Winter Wheat in Denmark. DJF Report Plant Science No 147, Aarhus University, Denmark, pp. 105-119.

Schjønning, P., Green, O., Birkmose, T.S., 2010b. Soil compaction effects on the development of winter wheat yields in Denmark. In: Petersen. J., Haarstrup, M., Knudsen, L., Olesen, J.E., (Eds.), Causes of Yield Stagnation in Winter Wheat in Denmark. DJF Report Plant Science No 147, Aarhus University, Denmark, pp. 121-138.

Six, J., Ogle, S.M., Breidt, F.J., Conant, R.T., Mosier, A.R., Paustian, K., 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Glob. Change Biol. 10, 155-160.

Smith, K.A., Conen, F. 2004. Impacts of land management on fluxes of trace greenhouse gases. Soil Use Manage. 20, 255-263.

Smith, P., Poulson, D.S., Glendinning, M.J., Smith, J.U., 1998. Preliminary estimates of the potential for carbon mitigation in European soils through no-till farming. Glob. Change Biol. 4, 679-685.

Snyder, C.S., Bruulsema, T.W., Jensen, T.L., Fixen, P.E., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric., Ecosys. Envir. 133, 247-266.

Soane, B.D., Ball, B.C., 2009. Development of no-till versus ploughing in Western Europe and relevance to crop production and environmental concerns. Proceedings of 18th Int. Conf., Int. Soil Tillage Research Org., Izmir, Turkey, (Supplement), Paper T1-064, pp. 1-16.

Sombrero, A., De Benito, A., 2009. Soil carbon accumulation in a ten-year study of conservation tillage and crop rotations in a semi-arid area of Castile and Leon, Spain. Proceedings of 18th Int. Conf., Int. Soil Tillage Research Org., Izmir, Turkey, Paper T5-004, pp. 1-10.

Sombrero, A., de Benito, A., 2010. Carbon accumulation in soil. Ten-year study of conservation tillage and crop rotation in a semi-arid area of Castille-Leon, Spain. Soil Tillage Res. 107, 64-70.

Spargo, J.T., Alley, M.M., Follett, R.F., Wallace, J.V., 2008. Soil carbon sequestration with continuous no-till management of grain cropping systems in the Virginia coastal plain. Soil Tillage Res., 100, 133-140.

Strudley, M. W., Green, T.R., Ascough II, J.C., 2008. Tillage effects on soil hydraulic properties in space and time: State of the science. Soil Tillage Res., 99, 4-48.

Sun, B., Hallett, P.D., Caul, S., Daniell, T.J., Hopkins, D.W. 2010. Distribution of soil carbon and microbial biomass in arable soils different tillage regimes. Plant and Soil DOI: 10.1007/s1104-010-0459-2.

Tebrügge, F., 2001. No-tillage visions – protection of soil, water and climate and influence on management and farm income. In: Garcia-Torres, L., Benites, J., Martĩnez-Vilela, A. (Eds.), Conservation Agriculture – A Worldwide Challenge. World Congress on Conservation Agriculture, Vol 1, pp. 303-316.

Tebrügge, F., Böhrnsen, A., 1997a. Crop yields and economic aspects of no-tillage compared to plough tillage: Results of long-term soil tillage field experiments in Germany. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experience with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC Workshop-IV., Wissenschaftlicher Fachverlag, 35428 Langgöns, Germany, pp. 25-43.

Tebrügge, F., Böhrnsen, A., 1997b. Farmers' experiences with no-tillage production. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop IV, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 55-102.

Tebrügge, F., Düring, R.A., 1999. Reducing tillage intensity - a review of results from long-term study in Germany. Soil Tillage Res. 53, 15-28.

Tebrügge, F., Wagner, A., 1995. Soil structure and trafficability after long-term application of no-tillage. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experiences with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop II, Wissenschaftlicher Fachverlag, Giessen, Germany, pp. 49-57.

Triplett, G.B., Dick, W.A., 2008. No-tillage crop production: A revolution in agriculture! Agron. J. 100, S-153-S-165. [Supplement to Agronomy Journal]

Troeh, F.R., Thompson, L.M., 1993. Soils and Soil Fertility. Oxford University Press, New York, USA, 462 pp.

Tullberg, J.N., Yule, D.F., McGarry, D., 2007. Controlled traffic farming – From research to adoption in Australia. Soil Tillage Res. 97, 272-281.

Ulén, B., Aronsson, H., Bechmann, M., Krogstad, T., Øygarden, Stenberg, M., 2010. Soil tillage methods to control phosphorus loss and potential side-effects: a Scandinavian review. Soil Use Manage. 26, 94-107.

Ussiri, D.A.N., Lal, R., Jarecki, M.K., 2009. Nitrous oxide and methane emissions from long-term tillage under a continuous corn cropping system in Ohio. Soil Tillage Res., 104, 247-255.

Van Den Bossche, A., De Bolle, S., De Neve, S., Hofman, G., 2009. Effect of tillage intensity on N mineralization of different crop residues in a temperate climate. Soil Tillage Res. 103, 316-324.

Van Ouwerkerk, C., Perdok, U.D., 1994. Experiences with minimum and no-tillage practices in the Netherlands. I: 1962-1971. In: Tebrügge, F., Böhrnsen, A. (Eds.), Experience with the Applicability of No-tillage Crop Production in the West-European Countries. Proceedings of the EC-Workshop-I . Wissenschaftlicher Fachverlag, 35428 Langgöns, Germany, pp. 59-67.

Verch, G., Kächele, H., Höltl, K., Richter, C., Fuchs. C., 2009. Comparing the profitability of tillage methods in Northeast Germany - A field trial from 2002 to 2005. Soil Tillage Res., 104, 16-21.

Vinten, A.J.A., Ball, B.C., O'Sullivan, M.F., Henshall, J.K., 2002. The effect of cultivation method, fertilizer input and previous sward type on organic C and N storage and gaseous losses under spring and winter barley following long-term leys. J. Agric. Sci. 139, 231-243.

Vogeler, I., Rogasik, J., Funder, U., Panten, K., Schnug, E., 2009. Effect of tillage systems and P-fertilization on soil physical and chemical properties, crop yield and nutrient uptake. Soil Tillage Res., 103, 137-143.

Wagger, M.G., Cassel, D.K., 1993. Corn yield and water-use efficiency as affected by tillage and irrigation. Soil Sci. Soc. Am. J. 57, 229-234.

Wereszczaka, J., Niedźwiecki,J., Gołębiowski, B., Pużyński, S., 2009. The effect of 15 years of direct drilling application: Part I - S index and carbon sequestration. Proceedings of 18th ISTRO Conf., Izmir, Turkey, Paper T1-007, pp. 1-6.

West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. Soil Sci. Soc. Am. J. 66, 1930-1946.

Yamulki, S., Jarvis, S.C., 2002. Short-term effects of tillage and compaction on nitrous oxide, nitric oxide, nitrogen dioxide, methane and carbon dioxide fluxes from grassland. Biol. Fertil. Soils 36, 224-231.

Yang, X.M., Drury, C.F., Reynolds, W.D., Tan, C.S., 2008. Impacts of long-term and recently imposed tillage practices on the vertical distribution of soil organic carbon. Soil Tillage Res., 100, 120-124.