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Review

The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence

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Abstract

Conservation tillage (CT) is practised on 45 million ha world-wide, predominantly in North and South America but its uptake is also increasing in South Africa, Australia and other semi-arid areas of the world. It is primarily used as a means to protect soils from erosion and compaction, to conserve moisture and reduce production costs. In Europe, the area cultivated using minimum tillage is increasing primarily in an effort to reduce production costs, but also as a way of preventing soil erosion and retain soil moisture. A large proportion (16%) of Europe's cultivated land is also prone to soil degradation but farmers and governments are being slow to recognise and address the problem, despite the widespread environmental problems that can occur when soils become degraded. Conservation tillage can improve soil structure and stability thereby facilitating better drainage and water holding capacity that reduces the extremes of water logging and drought. These improvements to soil structure also reduce the risk of runoff and pollution of surface waters with sediment, pesticides and nutrients. Reducing the intensity of soil cultivation lowers energy consumption and the emission of carbon dioxide, while carbon sequestration is raised though the increase in soil organic matter (SOM). Under conservation tillage, a richer soil biota develops that can improve nutrient recycling and this may also help combat crop pests and diseases. The greater availability of crop residues and weed seeds improves food supplies for insects, birds and small mammals. All these aspects are reviewed but detailed information on the environmental benefits of conservation tillage is sparse and disparate from European studies. No detailed studies have been conducted at the catchment scale in Europe, therefore some findings must be treated with caution until they can be verified at a larger scale and for a greater range of climatic, cropping and soil conditions.

Keywords: Soil; Pesticides; Integrated farming; Pollution; Water; Europe

1. Introduction

Cultivation of agricultural soils has until relatively recently predominantly been achieved by inverting the soil using tools such as the plough. Continual soil inversion can in some situations lead to a degradation of soil structure leading to a compacted soil composed of fine particles with low levels of soil organic matter (SOM). Such soils are more prone to soil loss through water and wind erosion eventually resulting in desertification, as experienced in USA in the 1930s (Biswas, 1984). This process can directly and indirectly cause a wide range of environmental problems. To combat soil loss and preserve soil moisture soil conservation techniques were developed in USA. Known as 'conservation tillage'(CT), this involves soil management practices that minimise the disruption of the soil's structure, composition and natural biodiversity, thereby minimising erosion and degradation, but also

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water contamination (Anonymous, 2001). Thus, it encompasses any soil cultivation technique that helps to achieve this, including direct drilling (no-tillage) and minimum tillage. Other husbandry techniques may also be used in conjunction including cover cropping and non- or surface incorporation of crop residues and this broader approach is termed "conservation agriculture." In this paper, the impact of tillage is predominantly the main consideration and the term "conservation tillage" is used throughout to encompass all of these non-inversion, soil cultivation techniques, but because with no-tillage or direct drilling the soil remains uncultivated this may create different soil conditions and is referred to separately where applicable. The term "conventional tillage" defines a tillage system in which a deep primary cultivation, such as mouldboard ploughing, is followed by a secondary cultivation to create a seedbed.

CT is now commonplace in areas where rainfall causes soil erosion or where preservation of soil moisture because of low rainfall is the objective. World-wide, CT is practised on 45 million ha, most of which is in North and South America (FAO, 2001) but is increasingly being used in other semi-arid (Lal, 2000a) and tropical regions of the world (Lal, 2000b). In USA, during the 1980s, it was recognised that substantial environmental benefits could be generated through soil conservation and to take advantage of this policy goals were changed. These were successful in reducing soil erosion, however, the social costs of erosion are still substantial, estimated at $37.6 billion annually (Lal, 2001). World-wide erosion-caused soil degradation was estimated to reduce food productivity by 18 million Mg at the 1996 level of production (Lal, 2000b). However, the potential environmental benefits of changing soil management practices are now being recognised world-wide (Lal, 2000a).

In Europe, however, soil degradation has only recently been identified as a widespread problem. This may include loss of structure leading to compaction, a decrease in SOM and a reduction in soil organisms (Fig. 1). As a consequence moisture is not retained, anaerobic conditions may develop and processes such as nutrient recycling slow down. Retention of soil moisture is important if the extremes of drought and flood are to be avoided. Serious water erosion as a consequence of degraded soil conditions occurs on 12% of the total European land area and wind erosion on 4% (Oldeman et al., 1991). In some areas, such as around the Mediterranean, the potential for soil erosion is even higher, with 25 million ha suffering from serious erosion (De Ploey et al., 1991). Indeed, the average rate of soil loss in Europe is 17 Mg ha, and is also increasing, exceeding the rate of formation of 1 Mg

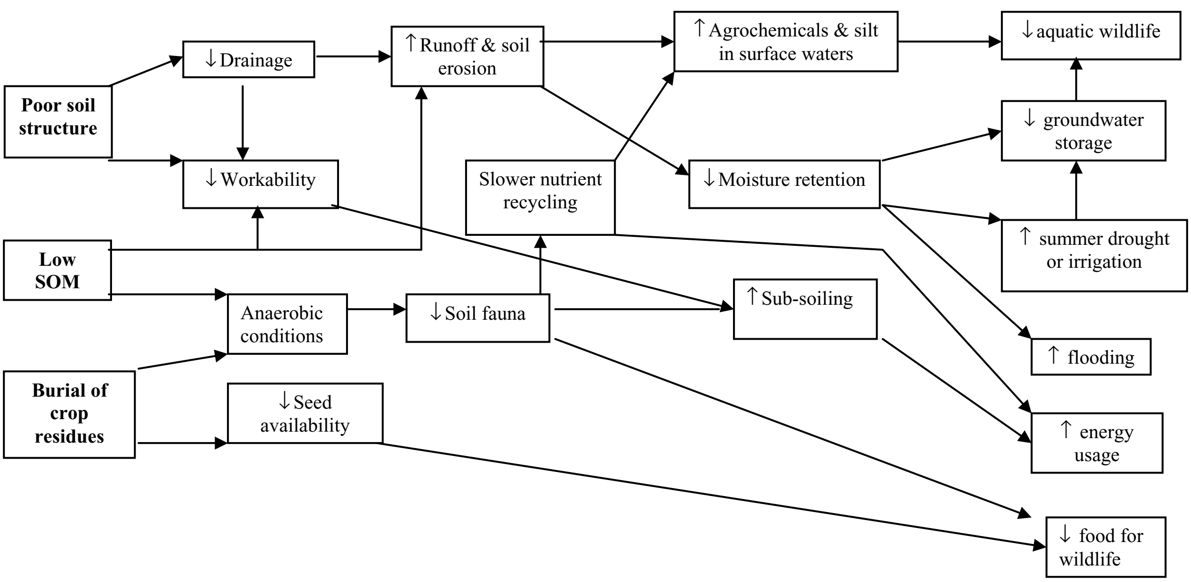

Fig. 1. Processes through which degraded soils affect the environment.

ha (Troeh and Thompson, 1993). Climate change may also exacerbate the problem as rainfall events have become more erratic with a greater frequency of storms (Osborn et al., 2000). In the more temperate areas the erosion risk is often underestimated. For example, in the UK 16% of the arable land has a moderate to very high risk of erosion (Evans, 1996). In 1999, the European Conservation Agriculture Federation (ECAF) was set-up to highlight the problems and promote conservation agriculture in the EU (ECAF, 2001). This is to be achieved on a national basis through the 11 national member organisations.

The degradation of soil conditions can affect the on-farm environment, although arguably the more threatening and costly effects are off-farm, because they include pollution of air and water. Therein lies the reason why the environmental consequences of soil management have been largely ignored, in Europe at least. Pollution of air and water away from the source remains unseen by the farmer, and consequently they are unmotivated to change practices for environmental reasons. Even on-farm, the link between soil management practices and environmental issues are difficult to observe unless the farm has vulnerable habitats and a topography favouring soil erosion. Where erosion occurs, farmers are often aware of the problem and take preventative action (Evans, 1996), however, if the erosion occurs but is less noticeable then farmers are unlikely to consider it. In addition, crop losses are perceived to be small, with only 5% of fields suffering losses greater than 10% (Skinner and Chambers, 1996). Indeed noticeable yield reductions may not be detected unless soil organic carbon (C) falls below 1%, a level only found in 5% of arable land in the UK (Webb et al., 2001). These losses are small in comparison to the damage caused to the environment and infrastructure (Foster and Dabney, 1995; Evans, 1996). For example in USA, the total annual on- and off-site costs of erosion were estimated at 85.5 € ha^{-1} (Pimentel et al., 1995). In Evans (1996), the off-farm costs of erosion for England and Wales these were estimated at US\$ 146–426 km^2 whereas those for USA were US\$ 1046 km^2 based on prices in the early 1990s. In some localities, flooding resulting from excessive runoff from agricultural land is of considerable concern. Many of the issues concerning erosion and runoff are addressed more fully by Evans (1996).

Conservation tillage has been heavily researched in North and South America, Australia and South Africa often with respect to semi-arid areas and this has been extensively published. The environmental implications of CT have been reviewed for USA (Soil and Water Conservation Society, 1995; Uri et al., 1998; Uri, 2001) and for Canada (McLaughlin and Mineau, 1995). In Europe, CT is a relatively new concept but if widely adopted it may have considerable environmental benefits. In this review, the environmental implications of CT are compared to conventional tillage-based systems drawing on findings from Europe where this exists otherwise information from other continents will be discussed.

2. Environmental impact of soil cultivation

2.1. Soil structure

The many different changes that occur in the soils physical and chemical composition following the implementation of CT have been widely researched and reported (e.g. Carter, 1994; El Titi, 2003) and will not be reviewed here. Instead whether these subsequently lead to environmental benefits will be examined in the context of these changes.

In arable soils, a complex range of processes are in operation as crop residues are broken down, nutrients recycled and the soil structure configured (Fig. 2). Many of the processes are interacting and a feedback mechanism may also occur, further encouraging a particular process. As a consequence, the soil's structural stability can have a substantial impact on the environment (Fig. 2). One of the most important components of the soil is the organic matter. This strongly influences soil structure, soil stability, buffering capacity, water retention, biological activity and nutrient balance ultimately determining the risk of erosion (Figs. 1 and 2). Erosion is considered to occur when the organic C content of the soil falls below 2% (Greenland et al., 1975; Evans, 1996). There is, however, evidence that over the last 40 years the amount of organic matter being returned to the soil has declined, primarily as a consequence of more intensive soil cultivation, the removal of crop residues, the replacement of organic manures with inorganic fertiliser, and the loss of grass leys from rotations. In addition, organic matter is being

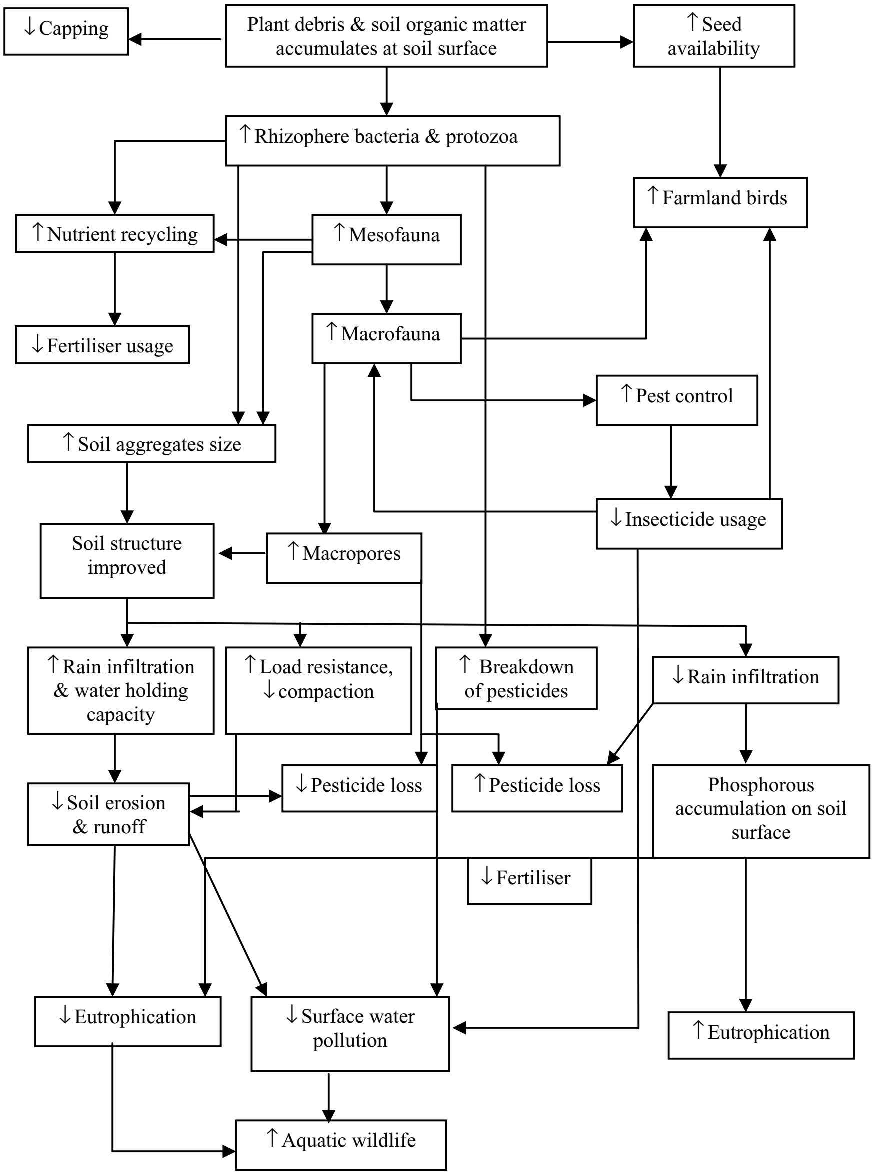

Fig. 2. Interactive processes through which conservation tillage can generate environmental benefits.

eroded from arable land to rivers disproportionately to its availability (Walling, 1990). Over this period losses of soil C were estimated at 30–50% (Davidson and Ackerman, 1993) and a large proportion of arable soils now contain less than 4% C. In the UK, for example, from 1978 to 1981 to 1995, the proportion with this level has increased from 78 to 88% (Anonymous, 1996). Others have demonstrated that over 20 years most agricultural soils lose 50% of soil C (Kinsella, 1995).

Such a collapse in soil structure is often combated by further cultivation rather than recognition that remedial measures are needed. The type of soil cultivation and the subsequent location of

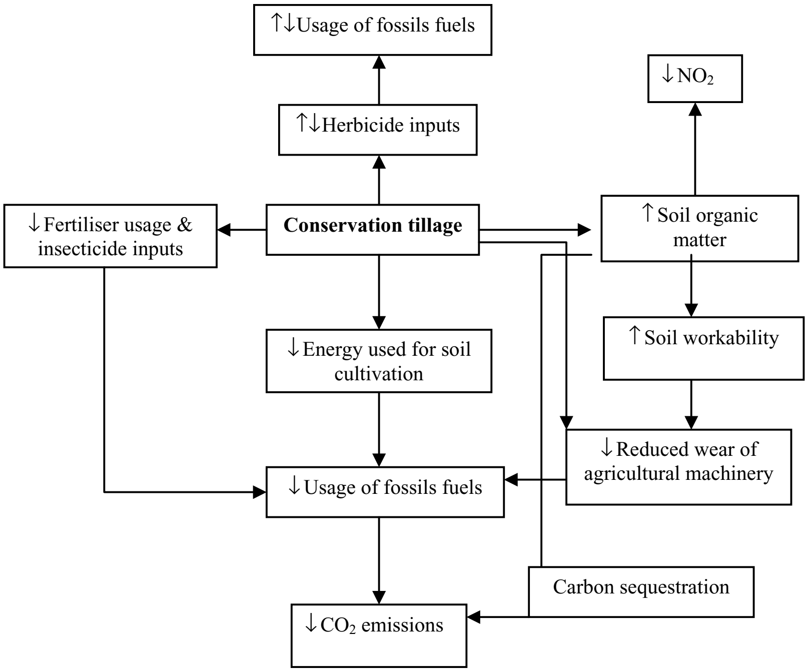

Fig. 3. Processes through which conservation tillage affects air quality.

crop residues also strongly influence the processes that occur. If CT is successful then the mechanism shown in Fig. 2 could be expected. This has the potential to generate many environmental benefits. However, the strength of soil structure created and the subsequent environmental outcome will also be strongly influenced by the moisture content and soil type.

Damage to soil structure can occur if cultivations are carried out when soil conditions are unsuitable and the outcome would be as depicted in Fig. 1. There is now also some evidence that long-term use of CT can in certain situations lead to soil compaction and thereby lower yields, increased runoff and poor infiltration (Hussain et al., 1998; Ferreras et al., 2000; Raper et al., 2000). Excessive wheel traffic can also cause compaction (Larink et al., 2001) but the risk of this occurring is lower where CT is used (Sommer and Zach, 1992; Wiermann et al., 2000). Indeed there is evidence that CT can be used to rectify soil compaction (Langmaack et al., 1999, 2002) especially if used in conjunction with sub-soiling and cover cropping (Raper et al., 2000).

2.2. *Water quality*

The method of soil tillage can have considerable influence on soil erosion, rain infiltration, runoff and leaching (Figs. 2 and 3). Associated with this movement of soil and water are agrochemicals, either bound to soil particles or in a soluble form. The contamination of surface waters with silt, pesticides and nutrients have been frequently found to damage these ecosystems (Uri et al., 1998). Contamination of marine ecosystems may also occur but this is beyond the scope of this review. Instead whether CT can help to reduce the risk of these pollutants reaching surface and ground waters is considered.

In northern Europe, inversion tillage is often the most appropriate cultivation technique allowing the infiltration of rainfall in the autumn, but runoff can occur as a consequence of compaction or capping. However, in some situations CT may be more appropriate as demonstrated in USA. CT was shown to reduce runoff by between 15 and 89% and within it dissolved pesticides, nutrients and sediments (Wauchope, 1978; Baker and Laflen, 1983; Fawcett et al., 1994; Clausen et al., 1996). In many cases, most of the runoff and sediment loss occurs during severe rainfall events (Wauchope, 1978). CT can also reduce the risk of capping (Gilley, 1995) but if conducted when soil conditions are unsuitable, compaction and smearing of the soil surface may occur increasing runoff and soil erosion.

Cultivation may also indirectly affect aquatic ecosystems. Cultivation affects the rate and proportion of rainfall infiltration and thereby groundwater recharge, flow rates in rivers and the need for irrigation (Harrod, 1994; Evans, 1996). Thus, soil cultivation also indirectly influences water resources because irrigation water is abstracted from ground and surface waters. In areas of low rainfall, CT helped retain water in the upper soil layers (Rasmussen, 1999) reducing the need for irrigation. In Australia, groundwater recharge was 19 mm per year higher where CT was used in conjunction with retention of stubbles, however this fell to 2.2–3.8 mm per year when even sub-surface tillage was used (OLeary, 1996). Likewise, direct drilling combined with stubble retention was shown to increase rain infiltration, leading to an increase in the depth at which soil was wetted whilst runoff was reduced compared to cultivated soils (Carter and Steed, 1992). In a semi-arid area of Spain, CT did not effect water storage efficiency when no-till, minimum tillage and sub-soil tillage were compared in a fallow-cereal rotation (Lampurlanes et al., 2002), however, there were some seasonal differences between the tillage treatments.

2.2.1. Nutrients

Eutrophication is a widespread throughout the world (Harper, 1992) and is considered to be a consequence of plough-based cultivation systems combined with high inputs of inorganic fertiliser and frequent point source pollution from stockyards, silage stores and manure pits (Anonymous, 1999). CT can prevent nutrient loss (Table 1) through the mechanism shown in Fig. 2 and this has been demonstrated (Skøien, 1988). However, if compaction occurs as a consequence of long-term use of CT, phosphate can accumulate on the soil surface increasing loss via runoff (Ball et al., 1997; Rasmussen, 1999) the risk being higher if phosphate applications continue (Baker and Laflen, 1983). The creation of more macropores may also encourage preferential flow and thereby leaching. In North America, eutrophication of the great lakes with phosphorus (P) is extensive. By increasing the use of CT over a 20-year period from 5 to 50% of the planted area, soil loss was reduced by 49% along with the transport of phosphates (Richards and Baker, 1998) but the concentration in runoff was higher, leading to an overall loss that was 1.7–2.7 times greater (Gaynor and Findlay, 1995). Fertiliser application rates were consequently adjusted and overall the total P loadings were reduced by 24%. Other authors have also recommended that adoption of CT requires a change in fertiliser application techniques and inputs (Gilley, 1995; Soileau et al., 1994).

The type of soil cultivation also strongly influences nitrate leaching but the evidence that leaching losses are higher for inversion compared to CT is contradictory. Higher leaching losses and deeper nitrate infiltration occurred with no-tillage (Dowdell et al., 1987; Eck and Jones, 1992). Similarly, Kandeler and Bohm (1996) reported higher N-mineralisation under no-till and CT. In contrast, others report no difference (Lamb et al., 1985; Sharpley et al., 1991) or lower nitrate

Table 1
Effect of tillage on soil erosion and diffuse pollution (source: Jordan et al., 2000)

Measurements	Plough	Non-inversion tillage	Benefit compared to ploughing
Runoff ($l\,ha^{-1}$)	213,328	110,275	48% reduction
Sediment loss ($kg\,ha^{-1}$)	2045	649	68% reduction
Total P loss ($kg\,P\,ha^{-1}$)	2.2	0.4	81% reduction
Available P loss	3×10^{-2}	8×10^{-3}	73% reduction
TON ($mg\,N\,s^{-1}$)	1.28	0.08	94% reduction
Soluble phosphate ($\mu g\,P\,s^{-1}$)	0.72	0.16	78% reduction
Isoproturon	$0.011\,\mu g\,s^{-1}$	Not detected	100% reduction

Comparison of herbicide and nutrient emissions from 1991 to 1993 on a silty clay loam soil. Plots 12 m wide were established and sown with winter oats in 1991 followed by winter wheat and winter beans.

leaching (Table 1; Jordan et al., 2000). With no-till and ridge-till NO_3–N concentrations were lower but under no-till the total NO_3–N losses were higher because the total volume of water moving through the soil was higher compared to conventional tillage (Kanwar, 1997), as suggested by Fawcett (1995). Multiple applications of N further reduced leaching.

Earthworms and thereby the density of macropores, may also play an important role because their numbers drastically increase under CT leading to improved drainage (Edwards and Lofty, 1982). As a consequence, when drainage occurs nitrates in the soil are by-passed reducing N concentrations compared to conventional tillage where the macropores have been destroyed. The greater density of macropores created under CT may also contribute N to leachates because they are lined with available nutrients extracted from the organic matter (Edwards et al., 1993). What occurs will depend on local soil and hydrological conditions.

2.2.2. Sediments

Sediment is a major riverine pollutant in many parts of Europe (Tebrügge and Düring, 1999) and was considered to be the most important contaminant of surface waters, while also causing the most off-site damage (Christensen et al., 1995). Indeed, 27–86% of eroding sediment leaves the field (Quine and Walling, 1993) and given the large areas of farmland throughout Europe is of considerable concern.

Depending on the exact technique, CT can substantially reduce soil erosion: direct drilling reduced soil erosion by up to 95% (Towery, 1998) while CT achieved a reduction of 68% (Table 1). In USA, sediment loss was reduced by 44–90% (Baker and Laflen, 1983; Fawcett et al., 1994) and by up to 98% when CT was adopted across a whole catchment (Clausen et al., 1996). In a 15-year study comparing different CT techniques, sediment loss was 532,828 and 1152 kg ha^{-1} per year for no-till, chisel-plow and disk, respectively (Owens et al., 2002).

A reduction in the loss of sediments and subsequent improvement in water quality can benefit aquatic wildlife. Sediments have been shown to cause behavioural, sub-lethal and lethal responses in fresh water fish, aquatic invertebrates and periphyton (Alabaster and Lloyd, 1980; Newcombe and MacDonald, 1991). The most conclusive evidence that CT can benefit aquatic organisms originates from paired catchment studies conducted in USA (Sallenave and Day, 1991; Barton and Farmer, 1997). Within each catchment, the land was either cultivated by conventional tillage or CT and the impact on the benthic invertebrates was monitored. The annual production of caddis fly was six times higher where CT was used (Sallenave and Day, 1991). Although the exact cause of the differences could not be identified, measurements of pesticides suggested two likely causes. The first was that the algal food supplied of the caddis flies was lower in the conventional tillage catchment because atrazine levels in ambient water and storm runoff were higher and for longer periods of time. A greater proportion of the applied atrazine reached the water and applications of other herbicides were also greater in the conventional tillage catchment. Secondly, the quantity of organophosphate insecticide applied to the conventional tillage catchment was greater and along with increased runoff may have lead to higher concentrations in the river, although this was not measured. Likewise, Barton and Farmer (1997) found that where CT was practised the streams supported a greater diversity of Insecta, specifically Emphemeroptera, Plecoptera and Trichoptera, and the fauna was akin to that found in clean water. Total numbers of invertebrates were also higher. Fewer Mollusca, Annelida and Crustacea occurred compared to where conventional tillage was used. A number of factors were considered responsible. The settling of fine sediments in the stream bed may have prevented colonisation by larger invertebrates in the conventional tillage catchments and lead to a greater abundance of infaunal species (Tubificidae and Chironomini). CT also enhanced the hydrological stability and consequently base flow was higher and the period of flow longer (Barton and Farmer, 1997) determining the time over which favourable conditions for colonisation and reproduction were available.

2.2.3. Pesticides

CT can influence the environmental impact of pesticides in two ways (Fig. 2). Firstly through modification of the soil structure and functional processes that consequently affect the fate of pesticides once applied. Secondly by influencing the levels of crop pests, diseases and weeds and thereby the need for pesticides.

Table 2
Factors influencing the fate of pesticides in soil

Factors	Determining properties	Controlling factors
Pesticide type	Soil adsorption, solubility, volatility, persistence	Environmental conditions: soil type, microbial activity, SOM content
Soil properties (physical, chemical, biological)	SOM content, moisture level, biomass, soil pore connectivity, pH	Cultivation, crop rotation, rainfall, temperature
Environmental conditions	Temperature, rainfall	Geographic location
Site characteristics	Topography, hydrology, soil type, depth to groundwater	Cultivation, drainage system

The fate of pesticides, once they have been applied, is highly complex and dependant on many interacting factors, such as the properties of the pesticide, soil properties, environmental conditions and the site's characteristics (Table 2). Pesticides may cause acute and chronic effects on non-target organisms before they are broken down into harmless compounds, thus their persistence in the soil is a key determinant of their environmental impact. The movement of pesticides through soil was reviewed by Flury (1996). Pesticides may also enter surface waters via runoff or leaching, indeed 50% of samples taken from rivers in USA were toxic (MacDonald et al., 2000). These authors developed and evaluated sediment quality guidelines for a variety of pollutants found in freshwater ecosystems but this approach has yet to be applied in Europe.

The effects of tillage on the leaching of pesticides was reviewed by Rose and Carter (2003) and although they concluded, as did Flury (1996) that cultivations were an important determinant of pesticide leaching losses, the effect of adopting CT was highly variable. CT may increase the risk of leaching, particularly of herbicides because usage may increase when combating grass weeds, especially during the early transition years, but may eventually be lower (Elliot and Coleman, 1988). Moreover, the increase in soil macropores facilitates more rapid movement of water and the pesticides within, and subsequently into, watercourses (Harris et al., 1993; Kamau et al., 1996; Kanwar et al., 1997; Ogden et al., 1999) as occurred with no-till in USA (Isensee et al., 1990; Smith and Chambers, 1993). The macropores created by earthworms may prevent this occurring because they are lined with organic matter that retain agrochemicals, while also supporting a diverse and abundant microfauna which converts them into more benign chemicals (Edwards et al., 1993; Sadeghi and Isensee, 1997; Stehouwer et al., 1994). Similarly, adsorption and breakdown of pesticides was greater at the soil surface where higher SOM was created using CT (Levanon et al., 1994; Novak et al., 1996). In Germany, concentrations of trifluralin were under the limit of detection ($0.005\,mg\,kg^{-1}$) down to a depth of 30 cm in harrowed plots but were up to $0.019\,mg\,kg^{-1}$ in the ploughed plots increasing the risk of groundwater contamination (Berger et al., 1999).

The higher infiltration rates and the presence of crop residues associated with CT will ensure that runoff and sediment loss is reduced (Clausen et al., 1996; Pantone et al., 1996; Mickelson et al., 2001) and thereby lower the risk that pesticides will be transported directly into surface waters, as occurs with conventional tillage (Watts and Hall, 1996). However, this is not always the case and depends on the soil and rainfall conditions (Mickelson et al., 2001). In a study of paired catchments runoff and sediment loss were reduced by 64 and by 98%, respectively while total loss of atrazine and cyanazine were reduced by 90 and by 80%, respectively (Clausen et al., 1996). This demonstrated the importance of runoff in pesticide transport because although sediment bound concentrations of atrazine and cyanazine were higher under CT, pesticides were mostly present in the dissolved phase and the volume of runoff was considerably greater than that of sediment, as found elsewhere (Fawcett et al., 1994). SOM also appears to be a key component and because this only builds up slowly, the period over which the soil has been cultivated using CT techniques will influence the risk of pesticide loss.

CT can potentially reduce the risk of pesticides contaminating surface waters but if the value of CT is to be evaluated accurately then catchment wide studies are needed, however, such studies have only been conducted in USA. There direct drilling reduced herbicide runoff by 70–100% (Fawcett, 1995) and adoption of no-till reduced total runoff over a 4-year period to 10 mm compared to 709 mm from a watershed which was conventionally cultivated (Edwards et al., 1993). Likewise, leaching of isoproturon was reduced by 100% following the adoption of CT over a 6-year period (Table 1). Leaching may, however, be lower with conventional cultivation if a runoff event occurs shortly after tillage because infiltration of recently heavily cultivated soils is often high initially, then decreases as they compact (Baker, 1992; Zacharias et al., 1991). Rainfall can be the overriding factor in some situations, mitigating any changes to cultivation (Gaynor et al., 2000).

Further research is needed throughout Europe at the catchment scale to determine the fate of pesticides under CT and their subsequent impact on aquatic organisms. It is likely that results will vary between individual pesticides because of their differences in physio-chemical properties and hence response to changes in soil conditions (Sadeghi and Isensee, 1997) and quantity of crop residues as these can adsorb pesticides (Sadeghi and Isensee, 1996). Moreover, predicting the impact of pesticides in watercourses is highly complex because of for example: the variability in the fauna, soil types, pesticide concentration, exposure period and environmental conditions along with the pesticide degradation and the subsequent toxicity of any derivate chemicals.

Adoption of CT can also indirectly influence the risk of water contamination by reducing pest and disease levels (Andersen, 1999; Ellen, 2003) and theoretically pesticide inputs (Fig. 2). However, the evidence that this occurs in practice is contradictory (Sturz et al., 1997) and increases can occur, e.g. slugs (Andersen, 1999). There is also a greater risk that emergency applications of pesticides will be required (Hinkle, 1983). More frequent use of pesticides also increases the risk of resistance developing, especially with herbicides because of the greater reliance on these with CT compared to systems where cultivation is used for weed control.

2.3. *Air quality*

Soil tillage contributes to air quality in four ways as shown in Fig. 3.

2.3.1. *Direct machinery energy consumption*

The cultivation of soils through ploughing is the most energy demanding process in the production of arable crops. The diesel fuel used contributes directly to CO_2 emissions along with that used in the manufacture of the machinery. CT uses less energy while the wear and tear of parts is also lower. Adopting CT was estimated to save 23.8 kg C ha^{-1} per year (Kern and Johnson, 1993). Likewise, a full carbon cycle analysis revealed that the C emissions for conventional tillage, reduced tillage and no-till averaged over corn (Zea), soybean (*Glycine max*) and wheat (*Triticum aestivum*) were 69.0, 42.2 and 23.3 kg C ha^{-1} per year (West and Marland, 2002). They concluded that in the US a change from inversion tillage to CT will enhance C sequestration whilst also decreasing CO_2 emissions.

Methods of non-inversion soil cultivation (direct drill, disc + drill) clearly have lower energy usage than those based upon ploughing and/or power harrowing (Leake, 2000; Table 3). In addition sub-soiling, which also has a high energy usage, will be needed more frequently using conventional tillage (Stenberg et al., 2000). Systems based upon CT may, however, require additional operations such as in the creation of a stale seedbed, and may also lead to higher herbicide inputs (Table 4).

2.3.2. *Agricultural inputs*

Fossil fuels form the basis of many agrochemicals while energy is used in their manufacture, transportation and application. Additional energy may be used in the process of irrigation and production of seed. Adoption of CT can substantially change the crop input requirements by influencing fertiliser requirements, pest infestation levels and soil moisture as discussed in other sections of this paper (Fig. 2). The net carbon (C) production from agricultural inputs can exceed that used by machinery (West and Marland, 2002).

2.3.3. *Carbon emissions*

Intensive soil cultivations break-down SOM producing CO_2 thereby lowering the total C sequestration held within the soil. By building SOM the adoption of CT, especially if combined with the return of crop residues, can substantially reduce CO_2 emissions (West and Marland, 2002). In the UK, where CT was used soil C was 8% higher compared to conventional tillage, equivalent to 285g SOM/m^2.

Table 3
Machinery energy per tonne of crop produced under conventional and integrated farming (source: Donaldson et al., 1996)

Crop	Conventional farming		Crop	Integrated farming	
	Energy factor ($kW\,h^{-1}\,ha^{-1}$)	Average machinery energy per tonne ($kW\,ht\,Mg^{-1}$)		Energy factor ($kW\,h^{-1}\,ha^{-1}$)	Average machinery energy per tonne ($kW\,ht\,Mg^{-1}$)
LIFE Project					
1st W. Wheat	423	52.1	1st W. Wheat	383	55.6
W. Barley	420	57.2	W. Oats	328	53.7
Set-aside	358	–	1st W. Wheat	210	–
2nd W. Wheat	412	59.2	Set-aside	383	55.6
WOSR	441	187.8	WOSR	382	230.2
1st W. Wheat	423	52.1	W. Beans	384	165
Total	2477		Total	2070	
CWS Stoughton					
1st W. Wheat	473	50.4	1st W. Wheat	286	34.8
W. Beans	275	76.2	W. Beans	315	94.6
1st W. Wheat	506	54.9	1st W. Wheat	248	33.1
1st grass ley	673	22.6	1st grass ley	429	12.1
2nd grass ley	319	12.5	2nd grass ley	297	10.7
1st W. Wheat	410	48.2	1st W. Wheat	387	51.2
Total	2656	264.8	Total	1962	236.5

W: winter sown, OSR: oilseed rape.

In the Netherlands SOM was 0.5% higher using an integrated approach over 19 years, although this increase was also achieved because of higher inputs of organic matter (Kooistra et al., 1989). After 12 years of integrated farming incorporating CT, the SOM content was 25% higher at 0–5 cm and overall from 0 to 30 cm, 20% higher (El Titi, 1991). Similar increases in SOM in the upper surface layers were also found in a number of studies conducted throughout Scandinavia (Rasmussen, 1999). The residence time of SOM showed a two-fold increase under no-tillage compared to intensive tillage (Paustian et al., 2000). With CT, there is a risk that SOM may be reduced below this surface layer, but no evidence for this was found in Sweden (Stenberg et al., 2000).

Table 4
Energy used in husbandry operations (source: Leake, 2000)

Operation	Energy used (kW)
Mouldboard plough	175
Sub-soiler	163
Seed drill	35
Spring tine cultivator	21
Cambridge roll	14
Combine harvester	125
Power harrow	115
Disc	42
Direct drill seeder	40
Baling	49
Pesticide spraying	17
Fertiliser spreading	21

The time taken to increase SOM and the depth of these changes through the soil profile will depend on the amount of organic matter returned to the soil and the intensity of cultivation, in conjunction with soil type, especially clay content (Rhoton, 2000). Significant differences in SOM were detected in the top 2.5 cm after 4 years of CT. Other benefits included higher aggregate stability and lower modus of rupture, water dispersible clay and total clay, which reduced the risk of erosion. There are, however, concerns about the build-up of pests, weeds and diseases using CT and rotational ploughing is recommended although the benefits of CT are rapidly lost if inversion tillage is used (Pierce et al., 1994). In Germany, where soil had only received shallow cultivations for 20 years, the SOM was concentrated in the top 5 cm and in the 50 cm soil profile soil organic C was 5 $Mg\,ha^{-1}$ higher than the ploughed soil's level of 65 $Mg\,ha^{-1}$ (Stockfisch et al., 1999). Ploughing in the autumn instead of increasing SOM throughout the cultivated profile destroyed this stratification, and during the following mild winter, the surplus of soil organic C and N was completely decomposed. Adoption of CT may therefore be especially beneficial after a grass ley or pasture.

In 1997, the European Union signed the Kyoto protocol committing itself to a 8% reduction (compared to 1990 levels) in CO_2 emissions by the period 2008–2012. For the UK, the value of SOM as a C sink was been estimated at 6.6% of 1990 CO_2 emissions but this includes utilising a range of strategies (Smith et al., 2000). The potential of each of these was estimated in Tg per year as follows: use of CT (3.5); animal manures (3.7); sewage sludge (0.3); cereal straw incorporation (1.9); extensification (3.3); natural woodland regeneration (3.2); and biocropping (4.1). The value for CT is a combination of reduced fossil fuel emissions and SOM accumulation, assuming use on 80% of the cereal area, which is equivalent to 37% of arable land. However, it is unlikely that the above strategies would be used in isolation but as a combination of practices, which will increase the potential for C mitigation. Moreover, the levels achieved will vary according to the rotation, soil type and equipment used.

The potential to reduce atmospheric CO_2 through the adoption of CT is therefore quite considerable. In Europe, it was estimated by Smith et al. (1998) that 100% conversion to no-till could offset all fossil fuel-carbon emissions from agriculture. The management of agricultural soils will be important in achieving the goals set under the Kyoto Protocol.

2.3.4. *Other greenhouse gases*

Tillage may affect the production of nitrous oxide through it's effect on soil structural quality and water content (Ball et al., 1999). De-nitrification in anaerobic soil and nitrification in aerobic soil produce nitrous oxide, with the former being more important. Moisture increases emissions. Where no-tillage was used to establish spring barley (*Hordeum vulgare*) nitrous oxide emissions were high and were exacerbated by compaction and heavy rainfall (Ball et al., 1999). Soil practices that improve the diffusion of gas and drainage should reduce the production of nitrous oxide. CT may cause greater emissions in the short-term because of larger soil aggregates and low gas diffusivity combined with high water retention at the soil surface and a greater abundance of de-nitrifers (Aulakh et al., 1984). As soil structure improves, the potential for creating anaerobic conditions and nitrous oxide emissions is reduced (Arah et al., 1991).

2.3.5. *Total carbon budgets*

If the full impact of a change in tillage on C budgets is to be evaluated, the energy usage of the whole production process must be evaluated. When the energy usage of two integrated farming systems utilising CT were compared to conventional systems based upon ploughing, total energy usage was 16 and 26% lower over a 6-year rotation (Table 3). However, the average yield was lower for comparable crops and consequently the machinery energy usage per tonne of crop was higher for the integrated approach in the LIFE Project. In contrast, at CWS Stoughton, where the same crops were produced under each system, the total machinery energy used per tonne of crop was lower using the integrated approach. A detailed C audit in USA revealed that the net C flux averaged across a range of crops was $+168\,\mathrm{kg\,C\,ha^{-1}}$ for conventional tillage compared to $-200\,\mathrm{kg\,C\,ha^{-1}}$ for no-till (West and Marland, 2002).

Fertiliser is the other main energy input and this can reach 50% of the total energy requirements (Leake, 2000). This can be reduced with CT, because less nitrate and P is lost by leaching, crop residues are normally incorporated and there is faster recycling of nutrients by an improved soil biota. Unfortunately, the rate of mineralisation can be highly variable between fields and consequently it is difficult to predict fertiliser requirements based upon mineralisation of SOM at present (Shepherd et al., 1996). This is a topic that requires further research.

3. Soil biodiversity

The structure of the soil and the diversity of organisms within it are inextricably linked because structural stability is determined by biological activity, along with biological, chemical and physical bonding and these are controlled by the approach to soil management and the soil type principally through the SOM (Fig. 4). Cultivated soils are generally regarded as having a reduced biodiversity compared to

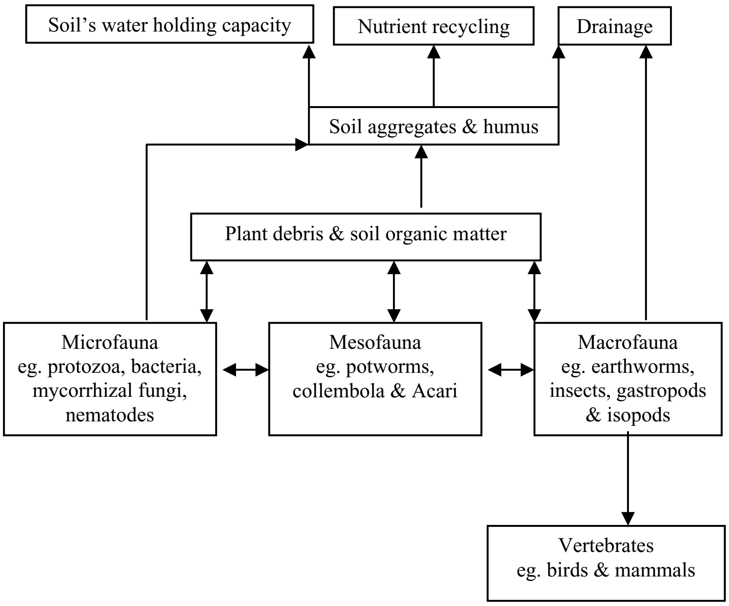

Fig. 4. Interactions between soil associated fauna and soil dynamics.

uncultivated soils (Benckiser, 1997). Soils cultivated by CT may lie somewhere in between the two extremes (Kladivko, 2001), their position depending on other factors such as inputs of inorganic and organic fertiliser, pesticides and the crop rotation.

The benefits of enhancing soil biodiversity have not been widely researched because productivity has been increased through the use of inorganic fertilisers, pesticides, plant breeding, soil tillage and liming. Most interest has been generated within lower input systems where the importance of a diverse and productive soil fauna has been recognised as being essential in the recycling of nutrients, improving soil structure and suppression of crop pests and diseases (Zaborski and Stinner, 1995). Detailed reviews on soil ecology are available but draw heavily on North American research with the focus on comparisons of no-till and conventional inversion tillage. These include: (1) affects of tillage on soil organism populations, functions and interactions (Kladivko, 2001); (2) the function of soil fauna and processes that occur (Lavelle, 1997); (3) the impacts of tillage on detritus food webs (Wardle, 1995).

The following sections review soil organisms and the implications of soil tillage; however, as studies on lower input systems have demonstrated, tillage cannot be examined alone as the maximum benefits are gained when CT forms part of an integrated approach to crop management (Holland, 2002). The levels of inorganic N inputs, pH and the levels and location of SOM within the soil profile determine soil stability, biodiversity and abundance. The higher level of SOM at the soil surface created using CT encourages a different range of organisms compared to a plough-based system in which residues are buried (Rasmussen and Collins, 1991).

The soil fauna were divided into three groups by Lavelle (1997):

1. Microorganisms (e.g. bacteria, mycorrhizal fungi, protozoa, Nematoda, Rotaroria and Tardigrada). They inhabit the soil solution and utilise organic compounds of low molecular weight.
2. Mesofauna (e.g. Enchytraeidae, collembola, Acarina, Protura and Diplura). These live in the pore system and feed upon fungi, decomposed plant material and mineral particles, or are predatory.
3. Macrofauna (e.g. Gastropoda, Lumbricidae, Arachnida, Isopoda, Myriapoda, Diptera, Lepidoptera, Coleoptera). These reside between the soil micro-aggregates feeding upon the soil substrate, microflora and fauna, SOM and surface flora and

fauna. They have the ability to move the soil and therefore affect soil porosity, water and air flow.

3.1. Microorganisms

These form a variety of functions in the soil most importantly in the recycling of nutrients whilst also forming the base of the food chain. Microbial biomass, diversity and overall biological activity are generally considered to be higher in soils cultivated using CT techniques compared to those receiving deep cultivations (Wardle, 1995; Heisler, 1998; Lupwayi et al., 2001). Long-term trials revealed that CT encouraged populations of rhizophere bacteria such as *Agrobacterium* spp. and *Pseudomonas* spp. and on a sandy loam soil this increased N^{-2} fixation and nodulation of pea plants (Hoflich et al., 1999). However, Lupwayi et al. (2001) revealed that the functional diversity of bacteria was no different between the whole soil (i.e. not separated into different aggregate sizes) for two soil types managed for 6 years under conventional tillage or zero tillage systems. However, in soil aggregates, diversity was significantly higher under conventional tillage than under no-tillage at barley planting time but by barley-heading stage, the reverse had occurred, and diversity tended to increase with increasing aggregate size. They attributed this to a decline in soil structure under conventional tillage.

The microorganisms also contribute to the formation of a stable soil structure (Gupta and Germida, 1988). With CT, the greater SOM near the soil surface encourages microbial activity leading to improved aggregate stability (Stenberg et al., 2000). In contrast, plough-based cultivation creates a more homogeneous soil texture as crop residues are distributed through the soil profile, and this favours bacteria, protozoa and bactivorous nematodes (Hendrix et al., 1986). With intensive tillage soil compaction is also higher, which reduces spaces between pores and changes the exchange and storage of gases, water and SOM (Brussaard and Van Faassen, 1994). Most studies on soil compaction, reviewed by (Bamforth, 1997) found reduced protozoan activity in the smaller pore spaces. This occurs because compaction creates anaerobic conditions that can be toxic to protozoa and are unfavourable to their bacterial prey. Similarly such conditions can be created around crop residues buried by ploughing.

Nematodes also perform a diverse range of functions in the soil although most is known about plant parasitic forms. The free-living forms contribute to nutrient recycling and may be responsible for 30% of the total N mineralisation (Griffiths, 1994). Because free-living nematodes depend on water for movement they are susceptible to soil structure, aeration and moisture, and therefore soil cultivation. Consequently opportunities exist to manipulate their abundance to achieve agronomic benefits but this approach has rarely been tried (Crossley et al., 1992), although it can be successful (Brust, 1991). After 8 years of integrated farming in the Lautenbach Project, parasitic and predatory nematodes were more numerous (El Titi and Ipach, 1989). In the short-term however, plant parasitic nematodes may dominate the fauna, whereas these are killed by ploughing (Lenz and Eisenbeis, 2000). The response to tillage can be variable between functional groups and will depend on other factors such as the cropping and abundance of residues (McSorley and Gallaher, 1994; LopezFando and Bello, 1995).

3.2. Mesofauna

The benefits of the mesofauna are primarily, as for the microfauna, in nutrient recycling but also in the creation of microaggregates that stabilise the soil structure. Some species also act as food for soil- and surface-dwelling arthropods. One of the most abundant groups is the Enchytraeidae (potworms) their abundance depending on levels of SOM. However, potworms were assumed to be relatively unaffected by tillage because of their small size and high reproductive rates and were even found to be more abundant in ploughed fields (Didden et al., 1994). However, where soils had become compacted potworm abundance was greater where CT was practised (Röhrig et al., 1998). With CT, they are most abundant near the soil surface but are more evenly distributed in ploughed fields.

Collembola and Acari (mites) also play a part in the nutrient recycling but this mainly occurs when inputs of inorganic fertilisers are replaced by organic manures that encourage their preferred fungal food (Rusek, 1998; Moore et al., 1990). These groups are more easily sampled so there is more evidence on the direct effects of tillage, however, the conclusions are inconsistent (Wardle, 1995). For example, no-tillage reduced the abundance of epigeic Collembola (Moore et al., 1984) and shallow tillage reduced Collembola (mainly Isotomidae and Sminthuridae) and mites below the depth of cultivation (at 30–33 cm). However, substantially higher numbers of Collembola and crypostigmatic mites were found at the soil surface (0–3 cm) (Bertolani et al., 1989; Vreeken-Buijs et al., 1994). Similarly, the diversity and abundance of mites and Collembola was higher in the integrated plots of the Lautenbach Project from 1980 to 1986 and this was attributed to the use of CT (El Titi and Ipach, 1989). Gasamid mites, which feed on nematodes, Collembola, Enchytraeidae, and immature Diptera, were especially high in the integrated plots and were assumed to be controlling pest species of nematodes (such as *Ditylenchus dipsaci* and *H. avenae*) and Collembola (*Onychiurus armatus*). The abundance of oribatid mites was higher with reduced and no-tillage compared to ploughing and species diversity was higher in no-tillage compared to ploughing (Franchini and Rockett, 1996).

A reduced microbial biomass and Collembolan density could be expected where soil structure is degraded because these groups are restricted by the pore space, with only smaller species surviving (Heisler and Kaiser, 1995; Larink, 1997). In addition, the vertical distribution of the microarthropods depends on soil tillage and compaction (Schrader and Lingnau, 1997) the higher density of macropores, which occurs with reduced tillage, facilitating the distribution of microarthropods.

3.3. Macrofauna

Lumbricidae (earthworms) modify the soils physical structure by the creation of burrows, which can penetrate the sub-soil and control infiltration and drainage, and combined with the binding ability of casts, decrease the risk of erosion (Arden-Clarke and Hodges, 1987). Transportation of soil by earthworms ensures mixing of organic matter, micro-organisms, spores, pollen and seeds and the creation of humus. Earthworms also directly alter the nutrient content of the soil by mechanically breaking down organic matter, encouraging microbial activity and ensuring mixing and as a consequence N is released. There is considerable evidence that earthworm populations are directly influenced by soil tillage, but the impact varies between species and according to the soil factors, climatic conditions and type of tillage (Chan, 2001). Inversion tillage, especially if followed by frost or dryness, exposes earthworms to predation and desiccation (House and Parmelee, 1985) and is especially damaging to deep burrowing (anecic) species (Kladivko et al., 2001). Rotary tillage is mechanically damaging (Edwards and Lofty, 1975). CT especially if combined with the return of crop residues and additional organic manures nearly always increases earthworm populations (Kladivko, 2001). Deep burrowing species (e.g. *Lumbricus terrestris*) are especially encouraged (Edwards and Lofty, 1982). Where CT was adopted for the integrated system, earthworm biomass when averaged over a 10-year period was 36% higher compared to ploughing (Jordan et al., 2000) while up to a six-fold increase was achieved in Germany (El Titi and Ipach, 1989). Earthworm populations may be especially low in drier climates but adoption of CT has been shown to increase populations substantially. In the Mediterranean climate of the Pacific NorthWest, earthworm populations were six times higher after use of CT for over 30 years compared to ploughed plots (Wuest, 2001).

The gastropods, isopods and myriapods are considered the most sensitive to soil cultivation and as a consequence, with the exception of slugs, are rare in agricultural soils (Wolters and Ekschmitt, 1997). Where present, they consume and bury green organic matter and their faeces encourage microbial activity leading to the formation of soil aggregates and humus. These groups are encouraged by CT because crop residues remain available on the soil surface and physical structure is retained, facilitating movement. Some of these groups (gastropods and diplopods), because of their poor dispersal ability, will be slow to reinvade following a switch to CT after a regime of intensive cultivation. The exception is slugs, which are often reported as requiring control when CT is adopted (Glen et al., 1996) and especially so if crop residues are incorporated (Kendall et al., 1995).

The soil supports a wide diversity of predatory arthropods, predominantly from the Coleoptera and Arachnida. These reside all or part of their lives within fields and on the whole are vulnerable to cultivation. Cultivation may effect survival directly by causing mortality whilst also having indirect effects by modifying habitat and the availability of prey. Ploughing creates a blank soil preferred by thermophilic species in the spring. In the longer-term, CT encourages grass weeds and retains organic matter on the soil surface, thereby increasing saprophytic and detritus feeding species upon which these predators depend. Many studies conducted in North America have specifically examined the effect of ploughing compared to conservation or CT on soil macro-arthropods. Fewer studies have been carried out in Europe but the results are similarly inconsistent, with increases with CT in the total number of arthropods (Kendall et al., 1995; Purvis and Fadl, 1996; Andersen, 1999; Holland and Reynolds, 2003), decreases (Andersen, 1999; Holland and Reynolds, 2003) and no effect being recorded (Huusela-Veistola, 1996; Holland and Reynolds, 2003). Individual species may vary in their response depending on their species-specific characteristics (Hance and Gregoire-Wibo, 1987; Kendall et al., 1995; Holland and Reynolds, 2003). Results were not always consistent between sites (Hance et al., 1990) and interactions often occurred with the cropping system and weed cover, these often exerting a greater effect than tillage (Hance, 2002; Andersen, 2003). There is some evidence that arthropod size can influence susceptibility with smaller arthropods, e.g. *Bembidion* species (Carabidae), favouring CT (Baguette and Hance, 1997); although the opposite was found by Kendall et al. (1995). This may be a result of their dispersal ability, as those which can quickly escape from the field following ploughing may be better able to survive (Luff and Sanderson, 1992). The time of cultivation is also important because different life stages may differ in their vulnerability. However, both carabid adults and larvae have been shown to tolerate cultivation (Hance and Gregoire-Wibo, 1987; Baguette and Hance, 1997).

Carabid beetles (Coleoptera: Carabidae) are often the most frequently studied organisms in these investigations because many species reside all year round within arable fields and they are sensitive to the type and timing of cultivations. The effects of cultivation were summarised by Kromp (1999), Holland and Luff (2000) and Hance (2002). Of the 47 taxa listed by Holland and Luff (2000), 20 had been shown to favour ploughed crops, 21 favoured CT, with six shown to favour both types of cultivation. They concluded that because different species respond according to their phenology, changing cultivation practices selects for those species best adapted to the new regime, and as a consequence, overall abundance may not differ but the species assemblage may change. Moreover, many of the conclusions are based upon data from pitfall traps which has many limitations the most important being that capture is related to activity (Adis, 1979). Firmer conclusions can be drawn where density is estimated using emergence traps (Purvis and Fadl, 1996; Holland and Reynolds, 2003). These studies indicated that ploughing adversely affected the survival of many carabid speies.

Rove beetles (Coleoptera: Staphylinidae) are also frequently found in arable farmland although few species overwinter as larvae within fields. Greater numbers of two species were found in reduced tillage compared to autumn ploughed plots (Andersen, 1999), however, no effect of ploughing was found by Holland and Reynolds (2003). Spiders are usually the most abundant arthropods within arable fields and some groups, e.g. wolf spiders (Araneae: Lycosidae) are relatively sensitive to disturbance (Holland and Reynolds, 2003). On the contrary, money spiders (Linyphiidae) were considered able to survive ploughing (Duffey, 1978), although this was not found by Holland and Reynolds (2003). It would be expected that spiders would readily colonise CT fields because they prefer an architecturally complex environment and this is better created by CT because there is a more complex litter layer, possibly higher wed density and more stable soil conditions (Rypstra et al., 1999).

The effect of cultivation on other arthropod groups has rarely been investigated. Arthropods important in the diet of pheasant chicks were assessed in no-tillage and ploughed or disced fields, but there were few differences (Basore et al., 1987). In contrast, cultivation was shown to reduce numbers of adult sawflies emerging from overwintering sites in the soil by up to 50% (Barker et al., 1999). Sawflies overwinter as pupae in the soil and so are particularly vulnerable to disturbance.

The timing of cultivations and subsequent seedbed preparations may also affect arthropod survival and it is likely that a combination of these factors, in addition to many others such as crop type, the type and quantity of organic manures, the disposal of crop residues and pesticide use (Holland and Luff, 2000) will together determine the ultimate macrofauna population.

Kladivko (2001) summarised the effects of no-tillage compared to conventional tillage on the above groups and concluded that larger species are more vulnerable to soil cultivations than the smaller ones because of the physical disruption and the burial of crop residues that consequently change food supplies and the soil's environmental conditions. In addition, the response to tillage becomes more variable as their size increases. The unpredictability of tillage effects is partly due to the varying levels of disturbance created in different studies (Wardle, 1995) but also because of the variability in the time of cultivation.

3.4. Flora

The abundance and diversity of weeds in arable fields in Britain changed dramatically following the development and widespread use of more efficient herbicides (Chancellor, 1977) but have remained relatively unchanged since the 1970s (Whitehead and Wright, 1989; Aebischer, 1991). CT can also change the species composition, favouring perennials and those annual species (mostly grasses) that do not require seed burial (Chancellor and Froud-Williams, 1986). However in Canada, Derksen et al. (1996) did not find an increase in grass weeds following a switch to CT, although in contrast to others (Lafond and Derksen, 1996; Légère et al., 1994). In the UK there have been reports of invasions from the margins of *Bromus* species and Apiaceae (Blackshaw et al., 1994; Theaker et al., 1995; Rew et al., 1996) and increases of *Alopecurus myosuroides* in winter sown cereals (Cavan et al., 1999). Indeed in Germany, after 4 years of integrated farming in which CT was used, the number of rare species had decreased at 90% of all sampling points where found. In the same period frequencies of rare weeds remained the same in the organic system, confirming that it was the adoption of CT that was responsible (Albrecht and Mattheis, 1998). When known densities of three weed seeds were sown, under CT *B. sterilis* increased 10-fold and *Galium aparine* increased when organic fertiliser was also used, but densities of *Papaver rhoeas* remained low (McCloskey et al., 1998). There is some evidence that there is an interaction between crop rotation and tillage. In wheat after maize the rank order of abundance was no-till then minimum tillage, followed by conventional tillage but the reverse was found in wheat after rape (Streit et al., 2000). Overall, which weeds predominate in a system will depend on many factors including tillage, rotation, herbicide inputs and weed species composition (Mulugeta and Stoltenberg, 1997).

3.5. Vertebrates

Farmland supports a diverse range of vertebrate wildlife and although many species rely upon the non-cropped habitat for food and cover, the cropped areas nevertheless provide essential foraging and breeding habitat for many species. CT may help in three ways: (1) the crop stubble provides cover in the winter and nesting habitat in the spring (2) crop residues and weeds if allowed to remain provide seed food in the winter (3) the higher levels of organic matter and weeds encourage arthropods in the summer (Fig. 2).

3.5.1. Birds

The intensification of agriculture is considered to be responsible for the decline of many bird species, although there may be other reasons (Baillie et al., 1997). The loss of stubbles during winter and the subsequent reduction in the availability of seed food is considered to be an important factor (Potts, 1998). Ploughed fields are universally avoided, probably because they provided little seed or invertebrate food with birds preferring those where the stubble remains (Wilson et al., 1996) even when seed densities were higher in ploughed compared to uncultivated fields (Hart et al., 2001). Those sown with crops also provide few resources because crop residues will have been buried and weeds controlled with herbicides (Hart et al., 2001). There is now some evidence that spring food supplies are limited (Draycott et al., 1997; Hoodless et al., 2001) and as a consequence fat reserves are low, which reduces the breeding success of seed-eating farmland birds. The soil surface is disturbed less when crops are established using CT therefore seed availability should be higher. The amount of spilt grain remaining after harvest was higher if the soil remained undisturbed after harvest (Baldassarre et al., 1983) and the crop residues left under CT were attracting more frequent visits by birds and a greater diversity (Castrale, 1985).

CT and especially direct drilling, combined with the use of non-toxic herbicides may also provide better cover and consequently nesting habitat for ground nesting birds compared to conventional tillage or where tillage was used to control weeds. In USA, this was shown to occur and as a consequence the abundance and diversity of species nesting was higher in the CT fields (Castrale, 1985; Basore et al., 1986; Rodgers and Wooley, 1983; Flickinger and Pendleton, 1994; Lokemoen and Beiser, 1997; Shutler et al., 2000) and was especially beneficial to bobwhite quail (Minser and Dimmick, 1988). The presence of crop residues was considered to be the most important factor influencing the selection of nesting sites, although the preferred amount of cover differed between species (Basore et al., 1986). Stubble height and total cover were considered to be important factors influencing the choice of nesting site (Flickinger and Pendleton, 1994). These were greater with CT in all seasons except spring when crop growth provided more cover in conventionally tilled fields. This lead to a greater abundance of all bird species but one, and overall diversity was higher in the CT fields. Despite the higher nest densities found with CT overall production was often below the levels needed to sustain populations. Birds attracted into CT fields because of the suitable cover but then their nests were more vulnerable to late tillage and drilling operations, however, the greatest loss was from predation (Basore et al., 1986; Lokemoen and Beiser, 1997). As a consequence Best (1986) suggested that CT created an ecological trap for nesting birds, drawing them away from more suitable uncultivated habitats. In these studies, in USA many of the crops from which these conclusions were drawn were mechanically weeded, however, in Europe fewer row crops are grown and mechanical weeding is relatively rare. Moreover, fewer species nest on the ground in crops.

In Europe, provision of adequate seed supplies over the winter and invertebrate food for chicks are considered to be two of the factors driving bird population dynamics (Benton et al., 2002; Robinson and Sutherland, 2002). The impact of CT on invertebrate food supplies has not always been clearly demonstrated (see Section 3.3). Many of the arthropods that are important dietary items for birds (Wilson et al., 1999) are also susceptible to tillage practices, e.g. Coleoptera, Diptera, Hymenoptera (sawflies and ants), Arachnida, Annelida, and Mollusca. Earthworm feeding species, e.g. lapwings, may be especially encouraged by CT if organic manures are also applied (Tucker, 1992).

The benefits of CT to farmland birds have rarely been investigated in northern Europe because research on tillage has mostly been conducted in experimental plots of insufficient size for bird studies. Where birds have been monitored the evidence is inconclusive. Skylark, yellowhammer, bluetit, robin and grey partridge were not shown to favour the integrated plots where CT had been used, compared to conventionally tilled plots (Saunders, 2000); although skylark, chaffinch, tree sparrow and yellowhammer were found in one plot in extremely high numbers during the winter following direct drilling with rye grass (Higginbotham et al., 2000). In southern Europe, the better feeding opportunities provided by CT encouraged greater numbers and diversity of birds (Valera-Hernández et al., 1997).

Other farmland birds rely to some extent on inversion tillage exposing invertebrate food in the autumn and again in the spring. These species include some whose numbers have more than doubled since 1968, e.g. carrion crow (Fuller et al., 1995). Whether less food is available under CT compared to other methods has not been adequately researched. Although studies of arthropods per se may reveal higher densities, their availability for birds may differ.

3.5.2. *Mammals*

Hares may also benefit from over-winter stubbles as a source of weed food. Small rodents and insectivores are largely confined to hedgerows and woodland in the winter, but may feed within arable fields during the summer, where with the exception of some crops they seek out weed seeds and arthropods (Flowerdew, 1997). Techniques which improve the densities of these foods are therefore likely to benefit small mammals, as has been shown with conservation headlands, which attracted wood mice (Tew et al., 1992). However, wood mice were shown to prefer conventionally tilled compared to CT plots in summer because of deep fissures providing cover (Higginbotham et al., 2000). Otherwise, there is little direct evidence from studies in Europe on the impact of CT on small mammals. In USA, rodents were more abundant and diverse where CT was practised because burrows could be established and the crop residues provided an abundance of food (Warburton and Klimstra, 1984). Populations of some species even established within fields as well as the edges and the populations were considered to be more stable compared to where conventional tillage was used (Johnston, 1986). In some situations, rodent populations may be sufficient to cause crop damage, but offsetting this is their potential to consume crop insect pests and weed seeds (Wooley et al., 1985).

4. Environmental benefits of adopting CT

The environmental benefits of adopting CT are wide ranging both on- and off-farm, as has been demonstrated in USA where CT has been practised for several decades. In comparison, less information is available from European studies, largely because until recently there has been little incentive to change for agronomic, economic or environmental reasons. Experimental systems developing and evaluating an integrated approach to arable production have been underway throughout Europe since the 1970s (Holland et al., 1994). Within these, CT has always been a key component, influencing nutrient recycling, pests and disease levels, soil moisture and the risk of runoff or leaching. Moreover, the benefits of adopting CT will be enhanced if they form part of a holistic approach to improve the functioning of agroecosystems, as defined in integrated farming (Holland, 2002). In these studies, comparisons were often made with conventional farming reliant on ploughing, and as a consequence they provide an indication of the potential benefits of CT, although the influence of tillage alone cannot be isolated.

Many of the off-farm benefits of CT may only be demonstrated if the practice is adopted across a large proportion of the cultivated land. In addition, most studies investigating diffuse pollution have been conducted at the plot or field scale and the relevance of these findings when extrapolated to the catchment scale has been questioned (Striffler, 1965). Wauchope (1978) suggested that using data from small plots to estimate pesticide losses from larger areas can overestimate the loss by two times. Quantifying diffuse pollution is, however, complex because of: (a) the wide range of pesticides in use and the type and timing of their application; (b) the range of soils types and their propensity to influence pesticide loss; (c) climatic conditions (Kookana and Simpson, 2000). Moreover, catchment-wide studies are needed for the evaluation of the impact on riverine and marine habitats, but such studies are both costly and difficult to establish and replication is needed if the above factors are to be considered. Studies at such a scale in USA, demonstrated the benefits of CT with runoff and sediment losses reduced by 64 and 99% respectively, along with less pesticide contamination of surface water (Clausen et al., 1996). The success of a catchment scale approach for reducing aquatic pollution was also demonstrated around Lake Erie leading to a reduction in eutrophication (Richards and Baker, 1998). However, in some situations CT can increase the total loss of phosphorus from the soil (Gaynor and Findlay, 1995).

The implementation of CT has not yet attracted much in the way of subsidies despite the apparent substantial economic reward in terms of preventing water and soil erosion, flooding and the need for water treatment. Instead, it is farmers who have recognised the financial gain to be achieved from reducing the cost spent in establishing crops. Research is now underway to ensure that the long-term viability of CT for crop production is ascertained, so that the new impetus does not fail as happened in the UK when direct drilling was introduced in the 1970s. However, some of the factors that prevented its uptake then are perceived to prevail today. These include the build-up of grass weeds and slugs, inconsistency of yield, expensive of equipment and difficulty of drilling through crop residues (Allen, 1975), although improvements in machinery have been made. Moreover, CT requires relatively dry soil conditions and wet weather can prevent drilling, whereas conventional tillage is more forgiving. Therefore, unless the farming operation is of sufficient size to allow the retention of the plough few farmers may be willing to commit fully to CT in the more temperate areas of Europe. However, financial support to assist farmers with the changeover in equipment, improvements to drilling machinery, along with specialist advice, may encourage more farmers to change and ensure that the most appropriate cultivation practices are adopted thereby ensuring that the most influential off-farm environmental benefits are achieved. It may, however, be the introduction of herbicide tolerant crops that will provided the greatest impetus for CT as effective weed control could be maintained, whilst substantially reducing crop establishment costs.

CT may, however, not always be the most appropriate cultivation technique and depends on the soil conditions, soil type and what is trying to be achieved. For example, atrazine leaching can be substantial after a maize crop but is most easily avoided by increasing soil permeability through ploughing to prevent runoff. The soil must also be free of compaction prior to the adoption of CT, otherwise this may be exacerbated under CT. There will then follow a transition period in which the soil structure will improve as SOM increases and macropores are established (Kinsella, 1995). During the transition period, the soil may be more prone to compaction and erosion, especially the weaker structured soils such as those containing a high proportion of sand. Indeed compaction is now more frequently being reported in the Americas after many years of CT (Ferreras et al., 2000; Raper et al., 2000) although this does not always occur (Lal, 1999). If compaction occurs the farmer is then faced with the dilemma of whether to plough to restructure the soil, but by doing so loosing SOM and killing soil fauna or to persist and suffer yield losses along with soil erosion and runoff. A combination of sub-soiling and cover cropping proved to be successful in alleviating compaction with the minimum amount of soil disturbance (Raper et al., 2000). In general, the management of soil using non-inversion requires greater skill by the farmer, access to drilling equipment that can cope with the crop residues and the ability to restrict cultivations to when soil conditions are suitable.

5. Conclusions

There is considerable evidence, predominantly from outside Europe that CT can provide a wide range of benefits to the environment and wildlife, some of these being similar to that provided by set-aside. The reforms of the Common Agricultural Policy (Agenda 2000) from compulsory to voluntary set-aside may result in a decline of this valuable habitat. CT has the potential to provide some of the benefits while also allowing farmers to continue cropping, but most will be achieved it CT is part of an integrated approach to crop management (Hinkle, 1983; Holland, 2002). In addition, by preserving soil and maintaining it in optimum condition crop yields are sustained thereby reducing the need to convert remaining natural habitats to agriculture.

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