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Examining the potential for climate change mitigation from zero tillage

Short title: Zero tillage in climate change mitigation

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SUMMARY

The benefits of reduced and zero tillage systems have been presented as reducing runoff, enhancing water retention and preventing soil erosion. There is also general agreement that the practice can conserve and enhance soil organic carbon levels to some extent. However, their applicability in mitigating climate change has been debated extensively, especially when the whole profile of carbon in the soil is considered, along with a reported risk of enhanced nitrous oxide (N₂O) emissions. The current paper presents a meta-analysis of existing literature to ascertain the climate change mitigation opportunities offered by minimizing tillage operations.

Research suggests zero tillage is effective in sequestering carbon in both soil surface and sub-soil layers in tropical and temperate conditions. The carbon sequestration rate in tropical soils can be about five times higher than in temperate soils. In tropical soils, carbon accumulation is generally correlated with the duration of tillage. Reduced N₂O emissions under long-term zero tillage have been reported in the literature but significant variability exists in the N₂O flux information. Long-term,
location-specific studies are needed urgently to determine the precise role of zero tillage in driving N₂O fluxes. Considering the wide variety of crops utilized in zero-tillage studies, for example maize, barley, soybean and winter wheat, only soybean has been reported to show an increase in yield with zero tillage (7.7% over 10 years). In several cases yield reductions have been recorded e.g. c. 1–8% over 10 years under winter wheat and barley, respectively, suggesting zero tillage does not bring appreciable changes in yield but that the difference between the two approaches may be small. A key question that remains to be answered is: are any potential reductions in yield acceptable in the quest to mitigate climate change, given the importance of global food security?

INTRODUCTION

The adoption of tillage practices for crop production date back to the invention of animal-drawn implements, with the benefits of tillage recorded as early as the 1800s (Gebhardt et al. 1985; Lal et al. 2007). In present-day conventional tillage systems, a mould board plough is typically used for primary tillage followed by the use of secondary tillage implements such as power harrows for seed bed preparation. In this approach it is usual that < 0.15 of crop residues are left on the surface (El Titi 2003) and the tillage depth is ≥ 20 cm (Jastrow et al. 2007). The environmental concerns about soil erosion, soil degradation and pollution of water brought about by tillage have resulted in the development of alternative tillage systems whose popularity have varied over time (Gebhardt et al. 1985) but are currently gaining more attention. Reduction of tillage in crop cultivation was first attempted primarily as a strategy to reduce soil erosion during the late 1950s in the US Corn Belt and Great Plains and increased in popularity globally especially after the discovery of the herbicides
atrazine and paraquat (Six et al. 2002b; Hermle et al. 2008). This and other different forms of tillage practices that reduce soil or water loss compared to ploughing have been referred to as ‘conservation tillage’ (Liu et al. 2013). Soil inversion in this context is not considered as conservation tillage, and shallow ploughing, if done, should be < 10 cm (El Titi 2003).

The current review focuses specifically on zero tillage (also called no tillage or direct drill) which aims to conserve soil and water by not disturbing the soil surface and leaving 0.30 or more crop residues on the surface (Erenstein & Laxmi 2008). Where relevant, a distinction is made from reduced tillage (also called minimum tillage), where only the upper 5 cm are disturbed (Wang et al. 2006). In 1999, the area under zero tillage was about 45 million hectares (Mha) globally, of which 0.96 was in North and South America (Derpsch & Friedrich 2009). By 2007/08 this area had more than doubled to 111 Mha spread across all continents (Table 1) (Derpsch et al. 2010). The largest area was in South America (0.468), followed by North America (0.378) and the least in Africa (0.003) and Europe (0.011). Zero tillage practices have been widely documented for their benefits including protection of soil against erosion and degradation of soil structure (Petersen et al. 2011), greater aggregate stability (Zotarelli et al. 2007; Fernández et al. 2010), increased sequestration of carbon (Six et al. 2000a; West & Post 2002) and improved biological activity (Helgason et al. 2010). The reduced use of fuel in field preparations is a significant economic attraction to farmers and adds substantially to environmental protection (Petersen et al. 2008). Further emphasis has been given in recent years to the climate change mitigation opportunities by following zero tillage systems considering in particular the potential carbon (C) storage in soil and reduction in emissions of carbon dioxide (CO₂) (Peigne et al. 2007; Koga & Tsuji 2009; Farina et al. 2011).
It has recently been reported that zero tillage can bring about stratification of organic carbon at the soil surface (Baker et al. 2007) compared to the more uniform distribution of carbon typically found in conventionally tilled soils (Campbell et al. 2000), questioning the effective sequestration obtainable under zero tillage. The surface-accumulated crop residues under zero-tilled soils may decompose, releasing CO$_2$ to the atmosphere (Petersen et al. 2008). Crucially, climate change mitigation benefits, such as reduced CO$_2$ emissions by virtue of increased sequestration of carbon and increased methane (CH$_4$) uptake under zero tillage, could be offset by increased emissions of nitrous oxide (N$_2$O), a greenhouse gas (GHG) with high global warming potential (Six et al. 2002b, 2004; Chatskikh & Olesen 2007). The warming potential refers to the radiative forcing impacts of each greenhouse gas relative to CO$_2$, as detailed in IPCC (2001). Increased N$_2$O emissions have been related to enhanced denitrification under zero tillage, due to formation of micro-aggregates (<250 µm) within macro-aggregates (>250 µm) that create anaerobic micro-sites (Hermle et al. 2008), high microbial activity leading to high competition for oxygen (West & Marland 2002a) and a dense soil structure (Regina & Alakukku 2010). Soil structure and soil wetness exert a considerable role in GHG emissions from soil (Ball 2013). Avoiding tillage in crop production can also impact on crop yields and ultimately global food security (Huang et al. 2008). A yield reduction of 21 and 15% in wheat and barley, respectively, was reported over 6 years in zero-tilled soil compared to conventional tillage by Machado et al. (2007). Among other factors, the yield reduction with zero tillage has been mainly attributed to increased weed growth, which makes it necessary to apply more herbicides. The potential for any mitigation by zero tillage therefore needs to be considered together with its impact on crop yields, as climate change and global food security are intrinsically linked. The
objectives of the current paper were to evaluate zero tillage for: (i) mitigation of climate change by sequestration of carbon and by reducing or balancing emissions of major GHGs from the soil and (ii) its effect on crop yield.

MATERIALS AND METHODS

For the current study, data sets pertaining to carbon storage in soils and crop yield under zero tillage were compiled.

Datasets on soil organic matter

A total of 49 data sets were collected from peer-reviewed research papers using the search term ‘zero (or no) tillage and carbon’ in Web of Science. Only those papers with paired conventional tillage (CT) and zero tillage (ZT) treatments were selected (Table 2). The C data were reported in t/ha. When only carbon concentrations were reported, bulk density values were used to convert carbon content to carbon stock using the following equation.

\[
t_{\text{C per ha}} = \frac{%C \times \text{bulk density} \times \text{soil depth} \times 100}{100}
\]  

Note here that zero tillage tends to result in denser soils with higher bulk densities (Mangalassery et al. 2014), hence soil profiles of the same depth will contain a greater soil mass in zero-tilled soils (Powlson & Jenkinson 1981; Ellert & Bettany 1995): this has implications for C content calculations. Specifically, basing the calculations on depth may result in an over-estimation of the positive effect of zero tillage on soil C stocks. Indeed using data from Ellert & Bettany (1995), depth-based calculations resulted in estimates of C stocks c. 16% higher than mass-based calculations.
Yield data sets

A review of the existing literature was made to compile a data set for comparing crop yield under zero tillage and conventional tillage. Sixty one datasets were used, from peer-reviewed research papers that made one-to-one comparisons with zero tillage and conventional tillage found using the search terms ‘crop yield and zero (or no) tillage’ in Web of Science (Table 3). The relative yield was then computed as follows.

Relative yield (%) = \[\frac{\text{Yield Zero Till in kg/ha}}{\text{Yield Conventional Till in kg/ha}} \times 100\]  

(2)

Statistical analysis

The locations of the studies reported in each paper were separated into tropical and temperate based on the climatic information provided in the paper and FAO agro-ecological zoning guidelines (Fischer et al. 2008). Regression equations were developed to explore the potential for carbon sequestration with zero and conventional tillage separately and under tropical and temperate conditions. The aim was to derive conclusions regarding the effect of duration of zero tillage on sequestration of carbon and soil depth on net sequestration carbon rate. The yield advantage or disadvantage under zero tillage with respect to conventional tillage was computed from the selected published literature. Linear regressions were carried out on the yield differences against duration of zero tillage. All the statistical analysis was carried out in Genstat (v. 14).
TILLAGE INFLUENCES IMPORTANT SOIL PROPERTIES

Zero tillage affects soil aggregation by decreasing oxidation of soil organic matter, which acts as a binding agent for macro-aggregates (Andruschkewitsch et al. 2014). Hence, water-stable aggregates (>250 mm) become more stable under zero-tillage systems (Tisdall & Oades 1980). Kasper et al. (2009) observed 18.2% of soil aggregates in the stable class under conventional tillage compared with minimum tillage which contained 37.6% stable aggregates. Continuous tillage practices also make aggregates susceptible to disruption under exposure to frequent wetting and drying cycles (Six et al. 2000b). The effect of wetting and drying cycles are more intensive on the top-soil and hence structural instability is generally greater in tilled soil where manual disaggregation of top soil occurs (Hernanz et al. 2002). Utomo & Dexter (1982) observed wet-dry cycles decreased the proportion of water stable aggregates > 0.5 mm.

Soil organic matter accumulates with zero-tillage practices, especially near the soil surface (upper 5 cm), when compared to conventionally tilled soils (Angers et al. 1997; Gosai et al. 2009). Under conventional tillage, crop residues are mixed with soil in the plough layer and hence nutrients are more or less evenly distributed (Wright et al. 2007), unlike zero tillage where an enhanced biochemical and physical environment at the surface would be expected, due to longer retention of crop residues there. Under minimum tillage, a reduction in soil organic matter turnover can affect net mineralization of nitrogen (Kong et al. 2009) and result in lower nitrogen availability for crops. Net immobilization of nitrogen has been reported during the transition periods to zero tillage (Jastrow et al. 2007). However, in the long term, the nitrogen concentration in the surface layer of zero-till soils has been found to be higher than in conventionally tilled soils (Ussiri et al. 2009). Zero-tilled soils have
also been reported to accumulate phosphorus and potassium at the surface (Wright et al. 2007). Franzluebbers & Hons (1996) observed greater surface accumulation of P, K, Zn and Mn in zero tilled soil than in conventionally tilled soils and Bauer et al. (2002) found enhanced accumulation of Ca and Mg in the upper layers of zero-tilled soils.

Tillage has both direct (by exposing them through inversion of soil) and indirect (by altering the soil microclimate) impacts on soil macro-organisms, with the effect being largely negative to their population (Roger-Estrade et al. 2010). In the long term, zero-tillage practices can be beneficial for earthworm populations compared with conventionally tilled soils due to enhanced availability of food resources (Eriksen-Hamel et al. 2009). An abundance of microbial biomass has been found in soils under zero tillage, including saprophytic fungi and arbuscular mychorrhizal fungi (Roger-Estrade et al. 2010). Helgason et al. (2010) found up to 32% higher microbial biomass under long-term zero-till systems than conventionally tilled soils.

CLIMATE CHANGE AND GREENHOUSE GASES

According to the Intergovernmental Panel on Climate Change (IPCC 2007b) the increased concentration of GHGs in the atmosphere is the major cause of global warming and associated climatic changes (Ugalde et al. 2007). The global atmospheric CO₂ concentration increased from 280 ppm in 1750 to 379 ppm in 2005, which has been attributed primarily to fossil fuel use and land use change (IPCC 2007b) with a total increase of 1.9 ppm per year. Apart from CO₂, the atmospheric concentration of CH₄ increased to 1774 ppb in 2005 from the pre-industrial value of
715 ppb (increase of 148%). Nitrous oxide continues to rise at the rate of 0.26% per year, measured at 319 ppb in 2005, 18% higher than its pre-industrial value (IPCC 2007b). Agriculture can act as both a sink and source for the GHGs of CO₂, CH₄ and N₂O based on the various mitigation strategies adopted. The IPCC (2007a) have suggested three broad mitigation options to reduce GHG emissions from agriculture; i) reducing soil disturbance, ii) enhanced sequestration of carbon in soil (West & Post 2002; Lal 2004a) and iii) reduced emissions of CO₂ during decomposition of crop residues triggered by ploughing and reduced use of fossil fuel in farm operations (West & Marland 2002a). Each of these is covered in further detail in the synthesis below.

SEQUESTRATION OF CARBON UNDER ZERO TILLAGE

Soils are the largest carbon reservoirs of the terrestrial carbon cycle (Lal 2004a), and increasing C sequestration in soil can mitigate increasing atmospheric CO₂ concentration (Kimble et al. 2001). A reduction in soil tillage is suggested to increase the rates of carbon sequestration by altering soil physico-chemical and biological conditions (Marland et al. 2004). Zero tillage is important for land management as it can help to sequester as much as 100–1000 kg carbon/ha/year (Lal 2004a). The sequestration of carbon under zero till management occurs faster under humid conditions, with Six et al. (2004) reporting sequestration within 5 years under such climatic conditions. Example sequestration rates obtained under various zero tillage studies are presented in Table 4. West & Marland (2002a) obtained a mean carbon sequestration rate of 340 kg/ha/year from 76 long term experiments for the plough layer of soil extending up to 30 cm over 20 years. Similarly a comparable sequestration of carbon was observed by Six et al. (2002b) in the upper 30cm of zero
tilled soil for both tropical (325 kg/ha/year) and temperate (113 kg/ha/year) conditions. The carbon sequestration capabilities increased considerably with an increase in duration of zero tillage, with the increment more evident under tropical conditions (Fig. 1, $P < 0.05$ for tropical and non-significant (NS) in case of temperate). The present analysis suggests the carbon sequestration rate under zero tillage of the top 25 cm soil (ploughing depth) was 864 kg/ha/year in tropical regions against 173 kg/ha/year in temperate soils (Fig. 2, $P < 0.05$ for tropical and $P < 0.001$ for temperate). The changes in carbon sequestration are also dependent on many other variables such as crop rotation, soil type (Gaiser et al. 2009) and soil drainage (Duiker & Lal 1999). McConkey et al. (2003) observed a linear relationship with clay content and increase in carbon stock under zero till, which was further confirmed by Grace et al. (2012) who recorded more than double the sequestration rate in clay soils compared to sandy soils in India. The ability to sequester carbon also depends on the initial carbon content at the initiation of zero tillage practices as there is an upper limit of maximum carbon that could be sequestered (Stewart et al. 2007). Therefore, it is crucial to consider these parameters when evaluating the benefits of zero tillage.

Longevity of sequestered carbon under zero tillage

Lal (2004b) suggested that carbon sequestration by zero tillage might be viewed as a short-term strategy only. An initial decline of soil carbon has been reported with zero tillage compared to conventional tillage due to the absence of incorporated residues and organic inputs into deeper layers of soil (Kong et al. 2009). After 5 years, de Rouw et al. (2010) reported a net loss of carbon (1.33 t/ha) under zero till in comparison to tilled soil in Laos. The initial delayed response to sequestration of carbon after conversion from conventional tillage was also reported by West & Post
(2002), who observed little or no increase during 2–5 years and then a large increase between 5–10 years. The time required to reach a ‘steady state’ in carbon sequestration varies with respect to climate, soil type and management practices and can range from 5 to 30 years according to the studies listed in Table 4. The initial soil carbon content in relation to the equilibrium level that a particular soil can achieve is important in deciding the effectiveness of zero tillage with respect to the sequestration (de Rouw et al. 2010). Angers & Eriksen-Hamel (2008) found a weak but significant correlation for soil organic carbon ($R^2 = 0.15, P \leq 0.05$) with the duration of zero tillage and hypothesized that the positive effect of zero tillage would increase with time. In the current analysis, carbon under zero tillage in tropical regions was significantly correlated with the time since conversion ($R^2 = 0.22, P \leq 0.001$), but this was not significant for temperate regions. This is in agreement with reports that in temperate soils, the time period to attain sink saturation is around 100 years, with lower values for tropical soils (20–50 years) (Lal 2004b; Smith 2004; Alvaro-Fuentes & Paustian 2011).

Physical aspects of carbon sequestration with zero tillage

Aggregation

Tillage generally reduces soil aggregation and consequently particulate organic matter content (Wright & Hons 2005). Under tillage, macro-aggregates are physically broken up due to shearing forces and by exposure to wet-dry and freeze-thaw cycles (Conant et al. 2007). Zero tillage is reported to increase sequestration of soil carbon, especially in the surface layer, and the major mechanism underlying such sequestration is an increase in micro-aggregation (Lal & Kimble 1997) and decrease in decomposition of
soil organic matter (Chatterjee & Lal 2009). Six et al. (1999) found proportions of crop-derived C in macro-aggregates were similar under zero till and conventional tillage, but proportions of crop-derived C were three times greater in micro-aggregates (250–2000 μm) from zero tillage than micro-aggregates from conventional tillage. Although the crop-derived carbon in macro-aggregates was similar in both conventional tillage and zero till, the zero till system had 28% more total organic carbon in all aggregate size classes compared to conventional tillage (Madari et al. 2005). Six et al. (2000a) developed a conceptual model to explain the C sequestration from zero tillage which hypothesized that tillage enhances macro-aggregate turnover and decreases the formation of new micro-aggregates. Under zero tillage the turnover of macro-aggregates decreases and the crop-derived carbon is sequestered within stable micro-aggregates and preserved within macro-aggregates. The improvement in soil aggregation and organic carbon preservation by zero tillage has been demonstrated by other workers, including Wright & Hons (2005) and Mrabet et al. (2001b). Six et al. (1999) attributed the decrease of C sequestration by tillage to increased macro-aggregate turnover. By following zero tillage the turnover of macro-aggregates are decreased and formation of stable micro-aggregates occur within macro-aggregates (Denef et al. 2007), which serve as long-term carbon stabilization sites. The increased macro-aggregation and its decreased turnover under zero tillage can cause a 1.5 times slower carbon turnover in temperate soils, due to carbon stabilization within micro-aggregates (Six et al. 2002 c, d).

Soil bulk density

Previous studies have indicated that continuous zero tillage practices over the long term reduce the bulk density of soil (Dam et al. 2005; Li et al. 2011). Lal et al. (1994)
found that after 28 years of maize and soybean, the lowest bulk density soil was in zero till soils. In another study, a continuous zero till system for 43 years had significantly decreased bulk density at the surface (0–15 cm) of a silt loam soil in Ohio ($P < 0.05$) with little effect on the subsurface layer (15–30 cm) (Ussiri et al. 2009). The reduction in soil compaction under zero tillage is mainly due to reduced traffic, additional crop residues at the surface (Jastrow et al. 2007) and increased biological activity provided by soil macro and micro fauna (Simmons & Coleman 2008) and changes in soil structure (Zhang et al. 2012). The lower bulk density is beneficial for easier root penetration into deeper layers, thereby increasing the crop-derived carbon input. This is specifically important in the case of deep-rooted plants, since photosynthates are translocated into the below-ground portions of the soil through rhizodeposition (Baker et al. 2007). The decreased soil bulk density can also aid the downward movement of surface-accumulated carbon (Luo et al. 2010), by preferential accumulation of plant residues moving in the soluble fraction (Angers & Eriksen-Hamel 2008). Blanco-Canqui et al. (2011) also found a moderate negative correlation between bulk density and soil organic carbon throughout a 1 m soil depth under zero till, indicating increased soil organic carbon could aid in reducing soil compaction. However, there are contrasting reports stating that continuous zero tillage can lead to increased soil strength and soil bulk density (Schjønning & Rasmussen 2000; Hernanz et al. 2009). Hill (1990) noticed increased bulk density and soil strength in the zero till treatments over an 11–12 year zero tillage experiment under continuous maize cultivation in Maryland, USA. López-Fando & Pardo (2011) found significantly higher surface bulk density under zero till soil than conventionally tilled soil over 20 years of experimentation in central Spain. It is possible that several factors contribute to increased bulk density with zero tillage systems but most likely is
the increased settling of soil due to lack of cultivation (Hermle et al. 2008), which can lead to soil consolidation (Peigne et al. 2007). Other possibilities include enmeshment of soil particles due to root action and impact of rainfall on the soil surface. However, the enhanced bulk density might not negatively impact on root growth if pore continuity is enhanced by creation of more biopores (Peigne et al. 2007), although further work is needed to explore the precise impact on pore geometry of zero tillage.

Soil structure and porosity

Soil structure is an important factor in determining the sequestration or decomposition of organic matter as it governs the physical space available for microorganisms, aiding their actions in terms of aeration, moisture supply (Strong et al. 2004) and mobility. Kay & VandenBygaart (2002) reported that zero tillage might cause a decline in total porosity but with increased porosity in the uppermost layer of the soil (upper 5 cm), near to the crop residues. Minimum and zero tillage practices initially lead to a decline in macro-pore volume in soil, which ultimately reduces diffusion of air into soil in comparison to conventional tillage (Schjønning & Rasmussen 2000). However, over time, there have been reports of increases in macro-porosity especially near to the soil surface (Zhang et al. 2007), due to the retention of stubble (Bronick & Lal 2005) and formation of macro-pores by the activities of soil organisms and plant roots (Kay & VandenBygaart 2002). Arshad et al. (1999) observed more micro-pores under zero tillage than conventional tillage. Smaller aggregates (50–250 μm or less), which can develop more readily when the soil is subjected to less disturbance, have a higher capacity for protection of organic matter than larger aggregates due to their smaller pore sizes (Bachmann et al. 2008). In undisturbed conditions, the organic matter lying between aggregates or inside larger aggregates are less prone to
microbial attack and therefore has increased longevity of residency (Chivenge et al. 2007).

Chemical aspects of carbon sequestration with zero tillage

Soil organic matter consists of different fractions with varying physico-chemical properties, each of which differs in turnover time (Del Galdo et al. 2003). Tillage alters aggregate dynamics and prevents the formation of stabilized carbon fractions such as intra-aggregate organic carbon (Six et al. 1999). The turnover of soil organic matter is dependent upon the type of organic matter in soil with the labile fraction requiring only 0.4 to 1.2 years for decomposition, whereas many years (400–2200) are required to decompose passive pools comprising of humic fractions, especially in cold, temperate soil (Lal & Kimble 1997). These include humic and fulvic acids and organo-mineral complexes. Microbially transformed substances are converted into humic forms through the intermediaries of quinones and amino compounds, the reaction being mediated by biological and inorganic catalysts (Stevenson 1994). The main determinant in this phenol oxidation is oxygen availability, which is directly related to cultivation practices in soil (Jastrow et al. 2007). The nature of association of organic matter with mineral particles heavily influences the chemical stabilization of carbon. Soils containing 2:1 clay minerals tend to preserve carbon more than those dominated by 1:1 clay minerals owing to their higher Cation Exchange Capacity (CEC) and specific surface available to 2:1 type of clay minerals (Six et al. 2002a). Thus zero tillage, by directly affecting the physical characteristics, has a significant impact on the chemistry of soil carbon dynamics.
Biological aspects of carbon sequestration with zero tillage

The number and diversity of soil organisms has been reported to increase with a reduction in tillage (Roger-Estrade et al. 2010). Soil microorganisms improve soil aggregation and thus indirectly influence carbon cycling by assisting with the physical protection of soil organic matter (Noguez et al. 2008). Peigne et al. (2007) found zero tillage systems contained more fungi than bacteria in the surface layers. Fungi have the capacity to efficiently sequester carbon in aerobic conditions and have greater carbon utilization efficiency than bacteria. Fungi attack more frequently on lignitic materials, producing monomers which are important constituents of humic materials and the residues of fungal death cells are resistant to microbial degradation (Jastrow et al. 2007). Mycorrhizal fungi are effective in increasing soil organic carbon through their effect on soil aggregation and are also efficient in securing carbon from the plant, thus adding extra carbon to soil organic matter (Manns et al. 2007). Tillage incorporates crop residues and places them close to decomposers while under zero tillage they are initially kept away from decomposers (de Rouw et al. 2010). In zero tillage, where disturbance is less, fungal hyphae grow and form bridge structures between soil and surface residues and form a major component of the soil fabric (Jastrow et al. 2007). Upon decomposition, these hyphal masses add to the soil carbon pool by way of the recalcitrant by-products of decomposition. The dry weight of hyphae in soil has been reported to be 0.03–0.5 mg/g and the amount of soil carbon derived by arbuscular mycorrhizal fungi is estimated to be in the range of 54–900 kg/ha for a soil depth of 30 cm (Zhu & Miller 2003). Frey et al. (1999) indicated fungal biomass in no till soils can vary from 6.8 to 74.3 µg C/g compared to 2.8 to 32.7 µg C/g in tilled soil. The contribution from microbial fungal carbon has been reported to be c. 0.08 to 0.2% of total C (Rillig et al. 2001).
Impact of soil depth on carbon sequestration under zero tillage

Previous work to estimate the carbon sequestration benefits of zero tillage have been criticized for being limited to the upper 20 cm of soil or less (Baker et al. 2007). In the current meta-analysis it was found that carbon sequestration with zero tillage takes place independently of soil depth (up to the maximum depth of 160 cm considered in the current study, although not all studies used in the meta-analysis considered as deep as 160 cm; Fig. 2). Significantly higher carbon was sequestered under zero tillage compared to conventional tillage, under both tropical ($R^2 = 0.30, P < 0.05$) and temperate conditions ($R^2 = 0.38, P < 0.001$) up to a depth of 160 cm. Multiple linear regression of carbon sequestration with depth and duration of tillage also indicated significant carbon increases under tropical ($P < 0.01$) and temperate conditions ($P < 0.001$). Angers & Eriksen-Hamel (2008) also found significantly greater soil organic carbon under zero tillage compared to full inversion tillage at depths up to 30 cm, by comparing 23 studies of zero tilled soils for more than 5 years to > 30 cm depths. The greater soil carbon at sub-surface depths recorded in full inversion tillage was not sufficient to offset the surface gain under zero tillage. Similarly, Six et al. (2002b) also found a net sequestration of carbon to a depth of 50 cm after 20 years of zero tillage. In a long-term tillage experiment over 17 years by López-Fando & Pardo (2011), a significant effect of zero tillage on carbon sequestration in the top 30 cm depth was found. This indicates that a net carbon sequestration is possible with zero tillage when the whole soil profile is considered, which might be due to the carbon addition to lower layers from the plant roots and leachates. It is worth noting, however, that care is needed when interpreting the C sequestration potential of different tillage systems since most studies do not account for the differences in soil
mass resulting from the different soil bulk densities with respect to tillage. This can result in an over-estimation of C stocks, as shown for zero tilled soils compared to tilled soils by Ellert & Bettany (1995).

Greenhouse gas emissions with zero tillage

*Carbon dioxide emissions under zero tillage*

Decomposition of plant residues and organic matter by the action of soil microbes and respiration of microbes and plant roots are the major sources of emissions of CO$_2$ in soil (Oorts *et al.* 2007). Immediately after tillage, emissions of CO$_2$ are known to rise. Chatskikh *et al.* (2008), in an experiment in Denmark, reported a 34% increase in emissions under tilled soil compared to reduced tilled soil. Ellert & Janzen (1999) showed that enhanced release of CO$_2$ immediately after tillage was associated with the release of CO$_2$ stored in soil pores and from stimulated biological production. The CO$_2$ flux soon after soil disturbance has been related to the depth of tillage and the degree of soil disturbance (Álvaro-Fuentes *et al.* 2007). Reduced turnover of soil organic matter through adoption of zero tillage can lead to decreased emissions of CO$_2$ (Six *et al.* 2000a). In south-western Saskatchewan, Canada, there was a 20–25% reduction in CO$_2$ flux under soils that had been zero tilled for 13 years compared to conventional tillage attributed to slower decomposition of the surface left crop residues under zero-tilled soil (Curtin *et al.* 2000). Mangalassery *et al.* (2014) have also shown significant reductions in CO$_2$ in zero-tilled compared to conventional tilled soils after 5–10 years post-conversion. In a long-term tillage experiment maintained for 25 years, Bauer *et al.* (2006) found the CO$_2$ flux from conventional tillage was higher compared to zero tillage, irrespective of timing. Zero tillage has
been reported to reduce CO$_2$ emission rate by 0.6 t C/ha/year compared to conventional tillage in a long-term experiment under maize (43 years) in the USA (Ussiri & Lal 2009). Whilst evidence points to less tillage leading to a significant reduction in CO$_2$ emissions, a long-term study by Oorts et al. (2007) found that, on more than half of the sampled days, zero tillage exhibited larger CO$_2$ emissions and they attributed it to the achievement of equilibrium between input and output under long periods (32 years) of zero tillage.

**Nitrous oxide emissions under zero tillage**

In contrast to CO$_2$ emissions, most research reports increased N$_2$O emissions under zero tillage compared to conventional tillage (Ball et al. 1999; Chatskikh & Olesen 2007; Oorts et al. 2007). This has frequently been attributed to decreased water-filled pore space and mineral nitrogen concentration (Oorts et al. 2007), reduced gas diffusivity and air-filled porosity (Chatskikh & Olesen 2007), increased water content (Blevins et al. 1971) and a denser soil structure (Schjønning & Rasmussen 2000; Beare et al. 2009) as a result of a lack of disturbance. Overall, increased N$_2$O fluxes reported with zero-tilled soils have been linked to the increased anaerobic conditions provided by the increased bulk density and decreased soil porosity due to soil consolidation (Ball et al. 1999). The physical characteristics of the soil in different layers, as modified by different tillage practices, may affect the flux of N$_2$O. If N$_2$O is produced at surface layers, which are frequently more permeable, the gas is likely to be emitted to the atmosphere, but if the point of production is in lower layers, overlaid by compact layers, the N$_2$O produced may be consumed within the profile over time. Although most reported N$_2$O emissions are quantitatively less in comparison to CO$_2$ emissions, N$_2$O assumes a greater significance due to its larger global warming
potential (296 times that of CO$_2$: IPCC 2001). Indeed, increased N$_2$O emissions have the potential to offset 75–310% of the climate change mitigation obtainable from the sequestration of carbon in soil (Regina & Alakukku 2010). The adoption of zero tillage over longer terms (20 years) has been reported to nullify this adverse effect on N$_2$O emissions, with lower N$_2$O emissions recorded under zero tillage than in tilled soils in humid climates and similar emissions under both tillage types in dry climates (Six et al. 2004). Similar reports were also made by Kessavalou et al. (1998) and Chatskikh et al. (2008), attributable to increased N$_2$O consumption in soil (Luo et al. 2010) although there is a lack of published long-term studies in this area. A further confounding issue is the uncertainty associated with estimation of N$_2$O which remains high in most experiments due to significant spatial and temporal variability (Chatskikh et al. 2008; Ussiri et al. 2009). It seems that further long-term location-specific studies combining different greenhouse gases and carbon sequestration are urgently needed to investigate the impact of zero tillage on N$_2$O flux, especially to investigate the time post conversion at which N$_2$O emissions from zero tillage fall below those from conventional tillage as reported by Six et al. (2004).

**Methane emissions under zero tillage**

Most previous studies indicate increased absorption of CH$_4$ in soils under zero tillage due to reduced surface disruption (Kessavalou et al. 1998; Regina & Alakukku 2010), greater pore continuity (developed over time) and the presence of more micro-sites for methanotrophic bacteria (Hütsch 1998). The increased soil bulk density reported with zero tillage might prevent the efflux of CH$_4$ leading to its oxidation within soil (Li et al. 2011). Long-term studies by Ussiri et al. (2009) indicated a net CH$_4$ uptake in zero-till soils in silt loam soil under maize in the USA (0.32 kg CH$_4$-C/ha/year for
zero till vs 2.76 kg CH₄-C/ha/year in conventional till). Continuous ecological disturbance under tillage can be detrimental to methane oxidizers. Most previous studies indicate that zero-tilled soils act as net sinks for methane. However, both increased and decreased CH₄ consumption has been reported in zero-till soils (Hütsch 1998; Venterea et al. 2005). If a zero-tillage system creates anaerobic micro-sites or creates conditions favourable to enhance water-logging conditions then it is likely that CH₄ production and emissions will increase.

Net emission of greenhouse gases

To obtain a realistic assessment on the potential of zero tillage for reducing GHG, the combined emissions of all major GHGs need to be considered. There are very few studies that have considered the global warming potential of different gases between conventional and zero-tillage systems. Whilst increased N₂O emissions from zero tillage have been reported, crucially some long-term studies have indicated a stabilization of N₂O emissions under reduced tillage over 20 years, especially in humid climates (Six et al. 2004). In a long-term study, Ussiri et al. (2009) observed lower total emissions of N₂O under 43 years of zero till in comparison to conventional tillage and the global warming potential under zero-till systems was found to be 51 to 58% less than under conventional tillage. Mangalassery et al. (2014) recently reported reductions of c. 20% under zero tillage, though the time since conversion was <10 years. A complete life-cycle analysis of a zero-till system and conventional till system was carried out by West & Marland (2002b) based on comparisons of 76 long-term experiments up to soil depths of 30 cm. After accounting for the CO₂ emissions from different inputs and production activities for maize, wheat and soybean in the US and comparing carbon sequestered under zero till, the net carbon sequestration reported
was 368 kg C/ha/yr. However, in an alternative study involving a global data analysis of zero till vs conventional tillage covering tropical and temperate soils it was found that, after accounting for the carbon sequestered and CH₄ taken up in soil, net sequestration was negative with an overall negative greenhouse balance of 214 kg CO₂- equivalents/ha/yr (Six et al. 2002b). However, Six et al. (2002b) only compared systems with tillage or zero-tillage elements, excluding experiments with the potential for additional carbon sequestration such as cover crops and crops in rotation. Robertson et al. (2000), after only 8 years of experimentation, reported a low net global warming potential under zero till (14 g CO₂- equivalents/m²/yr) compared to conventional till (114 g CO₂- equivalents /m²/yr). In most studies it would seem the slightly higher or comparable N₂O emissions under zero till is compensated for by the significantly enhanced carbon storage. For example, following a 30-year simulation experiment, Chatskikh et al. (2008) showed that zero tillage can decrease net GHG release by 0.56 t CO₂- equivalents/ha/yr compared to conventionally tilled soil while a field study over 43 years by Ussiri et al. (2009) found a decrease of 1.03 t CO₂- equivalents/ha/yr with zero tillage compared to conventional tillage (52% reduction).

The most consistent trend in the literature suggests that overall, zero tillage reduces GHG emissions in the long term (c. 20 years), but crucially some uncertainty still exists as to when the positive effects are first recorded and how long these effects can be observed. Large uncertainties still remain and further work is needed both to define the underlying mechanisms and understand the variation between agricultural systems.
Soil quality and yield responses under zero tillage

Current analysis suggests there is a lack of consistently reported effects of zero tillage on yield: 0.53 of publications examined in the current study reported an increase in crop yield with zero tillage, whereas 0.47 reported higher yield under conventional management (n=61). The most negative effects have been recorded in maize with an average of 0.36 reduction in maize yield by following zero tillage over 10 years reported in 15 publications (Fig. 3). The data on winter wheat (n = 20) generally suggested little effect on yield following the adoption of zero tillage over conventional tillage (1% reduction) (Fig. 3), though an 8% reduction in barley yield was observed over 10 years. However, the research in this area is conflicting: Machado et al. (2007) reported a yield reduction of 21 and 15% in wheat and barley, respectively, over 6 years, in zero-tilled soils compared with conventionally tilled soils. Declining cereal yields under short-term zero tillage practices have also been reported by Känkänen et al. (2011). A meta-analysis of 47 European studies by Van den Putte et al. (2010) comparing the crop yields under conservation tillage with conventional tillage reported yield reductions ranging from 0 to 30% depending on crop type, tillage depth, and texture of soil and crop rotation, with an average yield reduction of 4.5%.

The major constraint for realising good yields with zero tillage is the infestation of weeds (Vakali et al. 2011). Weeds compete with the seedlings for important resources necessary for growth such as light, water, nutrients and space, which may lead to poor germination, establishment and crop growth (Gruber et al. 2012). The surface retention of crop residues may also adversely affect the crop yield. Increased accumulation of crop residues, especially straw in poorly drained soils, can increase water-loggening and disease as well as reduce crop yield by affecting
germination (Wuest et al. 2000; Wang et al. 2006). It can potentially reduce the efficiency of applied fertilizers and pesticides, and affect drying and wetting regimes of soil (Carter 1994; Känkänen et al. 2011). The residue left on the surface may also affect nutrient availability to the crops, especially nitrogen due to immobilization.

Potentially, the negative effects of zero tillage on yield can be offset in the long term, following the development of an enhanced soil structure, which will support enhanced crop yields in the future. Wang et al. (2006) found increased yield under soybean of 7.7% with zero tillage over 10 years compared to conventional tillage (Fig. 3). The increased yields with zero tillage were mainly attributed to improvements in soil structure through non-disturbance and retention of crop residues at the surface. The positive aspects of surface retention of crop residues are a reduction in evaporation losses from soil, reduction in crust formation and enhanced protection from soil erosion (Guérif et al. 2001). In dry regions such as north-west China, crop residues left at the surface can be helpful for storing water (Huang et al. 2008) and in temperate regions it can prevent frost damage. Long-term tillage experiments in Switzerland over 15 years found comparable yields of wheat under reduced and conventional tillage systems (Anken et al. 2004), as also reported for maize yield during 11 years of experimentation in Canada (Dam et al. 2005), which is in contrast to many other studies (Chen et al. 2011). When combining zero tillage with retention of stubble, Huang et al. (2008) obtained 12.5% more yield from pea and 14% more spring wheat yield under conventional tillage over 4 years of experiments. They observed that the yield advantage of zero-tilled soils with respect to conventional soils disappeared when the stubble was removed, indicating the necessity of combining both zero tillage and residue retention to maximize productivity. This suggests there is potential for crop yields to be increased or
maintained under zero tillage by carefully addressing the yield-limiting factors such as weed growth, slow initial growth, nutrient deficiency, pest pressure and a hardened sub-surface (Lyon et al. 1998; Machado et al. 2007). It is worth noting that when considering the benefits of zero tillage over conventional tillage, there are considerations other than yield, as often a slight reduction in yield can be overcome by reduction in cultivation costs (Hobbs 2007).

The adoption of zero tillage in combination with other sustainable land use management options such as diversified crop rotation involving non-cereals (Van den Putte et al. 2010) has the potential to harness even better results. Infrequent tillage has been suggested as an alternative strategy to address the problem of compaction and weed growth. Conant et al. (2007) observed that such practices can sequester as much carbon as continuous zero-till systems, based on a modelling study. Indeed, field studies on periodic tillage by Yang et al. (2008) found tilling of a long-term zero-till soil (13 years) destroyed the surface stratification of soil carbon in the 0–5 cm layer, which was offset by soil carbon gains in the 10–20 cm depth. Similar results were reported by Kettler et al. (2000) and Pierce et al. (1994). However, such studies need to be conducted for each agro-ecological region to determine the fine balance between offsetting GHG emissions and maintaining good yields. The yield perspective is also important from a global change view point. Carbon sequestration may also be affected by biomass, which in turn is correlated with higher crop yield (de Rouw et al. 2010), and hence maintaining crop yield at satisfactory levels is important both for food security and climate change mitigation.

Zero tillage can be beneficial in sequestering carbon not only at the soil surface, but also in deeper layers in both tropical and temperate climatic conditions. The greatest concern regarding the ability to contribute to mitigating climate change
through zero tillage relates to the reported enhanced emissions of N₂O. However, declining N₂O emissions with zero tillage over longer timescales (e.g. 20 years) have been reported recently. In addition, when considered as a whole, most studies report a reduction in net warming potential following adoption of zero-tillage practices. Adopting further agronomic management along with zero-tillage strategies including weed control, crop rotation, cover crops and controlled traffic systems to control N₂O emissions may be the most beneficial ways in addressing the problem of yield reduction compared to environmental benefits.

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Table 1. *Area under zero tillage in different countries - Adopted from (Derpsch et al. 2010)*

| Country   | Area under zero tillage (’000ha) as of 2007-2008 | Area of zero tillage as % of cropped area* |
|-----------|-----------------------------------------------|------------------------------------------|
| USA       | 26500                                         | 16.3                                     |
| Brazil    | 25502                                         | 32.3                                     |
| Argentina | 19719                                         | 50.5                                     |
| Canada    | 13481                                         | 28.1                                     |
| Australia | 17000                                         | 35.4                                     |
| Paraguay  | 2400                                          | 60.2                                     |
| China     | 1330                                          | 1.1                                      |
| Kazakhstan| 1200                                          | 5.0                                      |
| Bolivia   | 706                                           | 17.4                                     |
| Uruguay   | 655                                           | 35.5                                     |
| Spain     | 650                                           | 3.8                                      |
| South Africa | 368                                       | 3.0                                      |
| Venezuela | 300                                           | 9.2                                      |
| Country      | Value | Percentage |
|--------------|-------|------------|
| France       | 200   | 1.0        |
| Finland      | 200   | 8.9        |
| Chile        | 180   | 10.1       |
| New Zealand  | 162   | 29.9       |
| Colombia     | 102   | 2.6        |
| Ukraine      | 100   | 0.3        |

**Total** 110755

*(FAO 2013)*
Table 2. *Global examples of Carbon stocks reported under conventional and zero tillage*

| Sl | Author         | Study area          | Soil texture | Years under zero tillage | Crops                      | Depth to which C reported | Carbon - Conventional (t/ha) | Carbon - under ZT (t/ha) | Climate     |
|----|----------------|---------------------|--------------|--------------------------|----------------------------|--------------------------|----------------------------|---------------------------|-------------|
| 1  | Sombrero & de  | Burgos, Spain       | Loamy sand in surface | 10 | Cereal – fallow, Cereal legume | 30 | 4.6 | 17.80 | Temperate |
|    | de Benito      |                     |              |                          |                            |                          |                            |                          |             |
|    | (2010)         |                     |              |                          |                            |                          |                            |                          |             |
| 2  | Deen & Kataki  | Ontario, Canada     | Silt loam    | 25 | Maize, Soybean | 60 | 36.7 | 39.0 | Temperate |
|    | (2003)         |                     |              |                          |                            |                          |                            |                          |             |
| 3  | López-Fando &  | Toledo, Central Spain | Loamy sand | 16 | Chick pea, barley | 30 | 26.5 | 32.6 | Temperate |
|    | Pardo          |                     |              |                          |                            |                          |                            |                          |             |
|   | Author          | Location         | Soil Type          | Crop Rotation | Yr 1 | Yr 2  | Yr 3  | Tempereate |
|---|----------------|------------------|--------------------|---------------|------|-------|-------|------------|
| 4 | Chatterjee & Lal | Michigan, US     | Clay loam          | Maize-soybean | 60   | 97.6  | 104.0 | Temperate  |
| 5 | Chatterjee & Lal | Ohio, US         | Clay loam, silty clay loam | Maize-soybean | 60   | 82.3  | 79.0  | Temperate  |
| 6 | Chatterjee & Lal | Ohio, US         | Loam               | Maize-soybean | 60   | 117.0 | 143.0 | Temperate  |
| 7 | Chatterjee & Lal | Ohio, US         | Silt loam          | Maize-soybean | 60   | 46.3  | 66.7  | Temperate  |
| 8 | Chatterjee & Lal | Pennsylvania, US | Loam               | Maize-alfalfa  | 60   | 96.4  | 83.4  | Temperate  |
|   | Authors          | Location          | Soil Type     | Crop(s)                   | Yield in t/ha | Nitrogen Use | Carbon Input | Climate Type |
|---|------------------|-------------------|---------------|---------------------------|--------------|--------------|--------------|--------------|
| 9 | Puget & Lal (2005) | Ohio, US          | Silty clay loam | Maize                     | 20           | 88.5         | 90.9         | Temperate     |
| 10| Dolan et al. (2006) | Minnesota, US     | Silt loam     | Soybean, maize            | 40           | 117.0        | 106.0        | Temperate     |
| 11| Kahlon et al. (2013) | Ohio, US          | Silt loam     | -                         | 15           | 21.4         | 27.6         | Temperate     |
| 12| Yang et al. (2008) | Ontario, Canada   | Clay loam     | Maize, maize-soybean rotation | 30           | 104.8        | 112.9        | Temperate     |
| 13| Yang & Wander (1999) | Urbana, US        | Silt loam     | Soybean                   | 30           | 46.6         | 58.5         | Tropical      |
| 14| Lou et al. (2012) | Jianping county, China | Sandy loam | Maize                     | 100          | 87.6         | 93.1         | Temperate     |
| 15| Lou et al.        | Changtu           | Loam          | Maize                     | 100          | 95.4         | 96.3         | Temperate     |
| ID  | Authors            | Location, Year | Soil Type | Rotation        | Yield 1 | Yield 2 | Yield 3 | Climate  |
|-----|--------------------|----------------|-----------|-----------------|---------|---------|---------|----------|
| 16  | Jemai et al. (2012) | Mateur, Tunisia | Clay loam | Wheat/faba bean | 50      | 83.9    | 80.2    | Temperate |
| 17  | Jemai et al. (2012) | Mateur, Tunisia | Clay loam | Wheat/sulla     | 50      | 83.9    | 73.1    | Temperate |
| 18  | Lal (1997)          | Ibadan, Nigeria | Sandy     | Maize           | 10      | 2.0     | 2.4     | Tropical |
| 19  | Larney et al. (1997) | Alberta, Canada | Sandy clay | Spring wheat - fallow | 15      | 27.1    | 29.2    | Temperate |
| 20  | Larney et al. (1997) | Alberta, Canada | Sandy clay | Continuous      | 15      | 31.0    | 33.0    | Temperate |
| 21  | Sisti et al. (2004) | Passo Fundo, Brazil | Clay     | Wheat-soybean   | 30      | 60.7    | 65.0    | Tropical |
|   | Author(s)       | Location                  | Soil Type       | Cover Crops                  | Treatment 1 | Treatment 2 | Treatment 3 | Temp. Type |
|---|----------------|---------------------------|-----------------|-----------------------------|-------------|-------------|-------------|------------|
| 22 | Metay et al. (2007) | Cerrados, Brazil          | Clay            | Leguminous cover crops      | 5           | 10          | 19.9        | Tropical   |
| 23 | Dendooven et al. (2012) | Central Mexico           | Clay            | Wheat and maize             | 19          | 60          | 76.8        | Tropical   |
| 24 | Varvel & Wilhelm (2011) | Lincoln, US Silty clay loam | Maize, soybean | 20                          | 60          | 90.5        | 114.4       | Temperate  |
| 25 | Varvel & Wilhelm (2011) | Lincoln, US Silty clay loam | Maize, soybean | 20                          | 90          | 104.8       | 138.6       | Temperate  |
| 26 | Varvel & Wilhelm (2011) | Lincoln, US Silty clay loam | Maize, soybean | 20                          | 120         | 123.3       | 165.4       | Temperate  |
| 27 | Dalal et al. (2011)  | Queensland, Australia     | Clay            | Wheat, barley               | 40          | 10          | 19.8        | Temperate  |
|   | Author(s)            | Location          | Soil Type   | Year | Crop Rotation | Yield (g/m²) | Temperature |
|---|----------------------|-------------------|-------------|------|---------------|--------------|-------------|
| 28 | He et al. (2011)     | Hebei province, China | Silt loam   | 11   | Summer maize, winter wheat | 30 | 6.1 | 6.6 | Temperate |
| 29 | Ussiri et al. (2009) | Ohio, US          | Silt loam   | 43   | Maize         | 30 | 44.8 | 80.0 | Temperate |
| 30 | Jantalia et al. (2007) | Planaltina, Distrito Federal, Cerrado, Brazil | Clay        | 20   | Soybean based rotations | 30 | 64.8 | 85.9 | Tropical |
| 31 | Bayer et al. (2000)  | Rio Grande do Sul State, Brazil | Sandy clay loam | 9    | Oat /maize    | 30 | 44.6 | 49.2 | Tropical |
| 32 | Bayer et al. (2000)  | Rio Grande do Sul State, Brazil | Sandy clay loam | 9    | Oat + common vetch /maize + cowpea | 30 | 50.2 | 56.6 | Tropical |
| Study   | Location                  | Soil Type | Year | Crop(s)                        | Yield | Yield/Maize | Yield/Soybean | Climate |
|---------|---------------------------|-----------|------|--------------------------------|-------|-------------|---------------|---------|
| 33 Fuentes et al. (2010) | Central Mexico Clay       | 16       | Maize | 20                            | 27.5  | 36.2        | Tropical      |
| 34 Fuentes et al. (2010) | Central Mexico Clay       | 16       | Wheat | 20                            | 27.3  | 40.0        | Tropical      |
| 35 Clapp et al. (2000)  | Minnesota, US Silt loam   | 13       | Maize, soybean, oats    | 15    | 49.7        | 50.4          | Temperate    |
| 36 Jantalia et al. (2007) | Planaltina, Distrito, Brazil Clay | 20 | Rice, soybean, maize       | 30    | 71.6        | 85.9          | Tropical      |
| 37 Varvel & Wilhelm (2011) | Lincoln, US Silty clay loam | 19 | Continuous maize and soybean | 150   | 131.6       | 171.3         | Temperate    |
| 38 He et al. (2011)      | Gaocheng, North China Silt loam | 11 | Summer maize and winter   | 30    | 19.6        | 18.2          | Temperate    |

60
| Study ID | Authors | Location | Soil Type | Duration | Crop Rotation | Yield | Probability | Climate Zone |
|----------|---------|----------|-----------|----------|---------------|-------|-------------|--------------|
| 39       | Sainju et al. (2002) | Georgia, USA | Sandy loam | 6 | Tomato or silage maize | 20 20.8 24.4 | Temperate |
| 40       | Kushwaha et al. (2001) | Banaras, India | Sandy loam | 1 | Barley | 10 9.9 12.0 | Tropical |
| 41       | Castellanos-Navarrette et al. (2012) | Central Mexico | Clay loam | 17 | Maize–wheat rotation | 30 35.4 44.1 | Tropical |
| 42       | Jarecki et al. (2005) | Ohio | Silt loam | 14 | Continuous maize | 50 51.4 54.7 | Temperate |
| 43       | Ernst & Paysandú (2005) | Paysandú, Clay loam | 10 | Wheat, barley | 18 47.3 51.8 | Temperate |
and oat for winter crops and maize, sunflower, sorghum, and soybean for summer crops

|   | Authors          | Location          | Soil Type | Spacing | Yield|  |  |  |
|---|------------------|-------------------|-----------|---------|-----|---|---|---|
| 44 | Mrabet et al.    | Sidi El Aydi, Morocco | Clay      | 11      | Wheat–maize, lentils fallow | 20 | 33.9 | 37.3 | Temperate |
| 45 | Abreu et al.     | Oklahoma, US      | Silt loam | 5       | Soybean–maize–wheat–soybean–maize | 110| 101.6|119.2 | Temperate |
| 46 | Abreu et al.     | Oklahoma, US      | Silt loam | 7       | Wheat–soybean–maize          | 110| 111.6|127.4 | Temperate |
| 47 | Abreu et al.     | Oklahoma, US      | Silt loam | 5       | Maize–wheat                   | 110| 104.5|116.3 | Temperate |
|   | 48 | Abreu et al. (2011) | US | Oklahoma, | Silt loam | 12 | Wheat/soybean/grain sorghum | 110 | 72.1 | 81.9 | Temperate |
|---|----|-------------------|----|-----------|-----------|----|----------------------------|-----|------|------|-----------|
|   | 49 | Zanatta et al. (2007) | US | Rio Grande do Sul State, | Sandy clay loam | 18 | Oat/maize | 30 | 41.8 | 46.5 | Tropical |
Table 3. Reported yields under various crops in zero till and conventional tillage systems, with increases and decreases associated with zero till highlighted

| Sl no. | Reference       | Study area               | Soil texture | Annual Rainfall | Years under zero till | Crop     | Yield Zero till (kg/ha) | Yield Conventional till (kg/ha) |
|--------|-----------------|--------------------------|--------------|----------------|------------------------|----------|-------------------------|---------------------------------|
| 1      | Chen et al.     | Northeast China          | Clay loam    | 530            | 6                      | Soybean  | 2659                    | 2441                            |
|        | (2011)          |                          |              |                |                        |          |                         |                                 |
| 2      | Su et al.       | Henan Province, China    | Loam         | 614            | 6                      | Winter   | 4679                    | 4125                            |
|        | (2007)          |                          |              |                |                        |          |                         |                                 |
| 3      | Hemmat & Eskandari | East Azerbaijan Province, Iran | Clay loam | 375            | 3                      | Winter   | 1435                    | 1014                            |
|        | (2006)          |                          |              |                |                        |          |                         |                                 |
| 4      | Vogeler et al.  | Braunschweig, Germany    | Silty loam   | 620            | 8                      | Winter   | 5790                    | 5680                            |
|        | (2009)          |                          |              |                |                        |          |                         |                                 |
| 5      | Vogeler et al.  | Braunschweig, Germany    | Silty loam   | 620            | 8                      | Field    | 2910                    | 2520                            |
|        | (2009)          |                          |              |                |                        |          |                         |                                 |
| 6      | He et al.       | Gaocheng in Hebei, China | Silt loam   | 494            | 11                     | Winter   | 6154                    | 5945                            |
|        | (2011)          |                          |              |                |                        |          |                         |                                 |
| 7      | Morell et al.   | Agramunt, Spain          | Sandy silt   | 435            | 10                     | Winter   | 1590                    | 1148                            |
|        | (2011)          |                          | loam         |                |                        |          |                         |                                 |
| Study Reference     | Location                  | Soil Type   | Clay (%) | CEC (cmol/kg) | Nutrient 1 | Nutrient 2 |
|---------------------|---------------------------|-------------|----------|---------------|------------|------------|
| Ekeberg & Riley (1997) | Southeast Norway Loam    | 415         | 9        | Spring barley  | 4310       | 4020       |
| Ekeberg & Riley (1997) | Southeast Norway Loam    | 415         | 9        | Spring wheat   | 3760       | 3280       |
| Cantero-Martínez et al. (2003) | Guissona, Spain Clay loam | <350        | 3        | Barley         | 4163       | 3803       |
| Cantero-Martínez et al. (2003) | Agramunt, Spain Sandy silt loam | <350        | 3        | Barley         | 3770       | 3230       |
| Buschiazzo et al. (1998) | Córdoba, Argentina Silt loam | 760         | 11       | Soybean        | 3230       | 2480       |
| Buschiazzo et al. (1998) | Córdoba, Argentina Silt loam | 760         | 11       | Sorghum        | 5720       | 4780       |
| Buschiazzo et al. (1998) | Buenos Aires, Argentina Sandy loam | 660         | 7        | Wheat          | 1600       | 1040       |
| Mrabet et al. (2000) | Casablanca, Morocco Clay | 296         | 3        | Maize          | 2470       | 2410       |
| Wang et al. (2012) | Luoyang, Henan, China Sandy loam | 570         | 6        | Winter wheat   | 4534       | 4413       |
| Franchini et al. (2012) | Paraná, Brazil Clay | 1651       | 23       | Soybean        | 3071       | 2496       |
| Study ID | Authors                  | Location                  | Soil Type                     | Depth (cm) | Nitrogen Application (kg/ha) | Winter Wheat (kg/ha) | Barley (kg/ha) |
|---------|--------------------------|---------------------------|-------------------------------|------------|------------------------------|----------------------|----------------|
| 18      | Kutcher & Malhi (2010)   | Saskatchewan, Canada      | Sandy loam                    | -          | 5                            | 3069                 | 2796           |
| 19      | Kutcher & Malhi (2010)   | Saskatchewan, Canada      | Clay loam                     | -          | 5                            | 3133                 | 2760           |
| 20      | Arshad et al. (1994)     | Alta, Canada              | Clay                          | 449        | 3                            | 1570                 | 1530           |
| 21      | Filipovic et al. (2006)  | north-west Slavonia, Croatia | Silt loam                    | 817        | 4                            | 5680                 | 5590           |
| 22      | Wang et al. (2011)       | Shanxi province, China    | Sandy loam                    | 520        | 5                            | 5347                 | 5185           |
| 23      | Karunatilak e et al. (2000) | Willsboro, New York     | Clay loam                     | -          | 7                            | 7260                 | 6420           |
| 24      | Sánchez-Girón et al. (2004) | Madrid, Spain       | Loam                          | 430        | 13                           | 3169                 | 3032           |
| 25      | Kumar et al. (2013)      | western Uttar Pradesh, India | Sandy loam                    | 800        | 3                            | 4490                 | 4090           |
| 26      | Lafond et al. (1992)     | Saskatchewan, Canada      | Clay                          | 534        | 3                            | 2070                 | 2039           |
| Study Reference            | Location               | Soil Type | Yield (kg ha⁻¹) | Study Year (Apr to Mar) | Crop Type     |
|----------------------------|------------------------|-----------|----------------|-------------------------|---------------|
| Hemmat & Eskandari (2004)  | Maragheh, Iran         | Clay      | 476            | 2                      | Winter wheat  |
| Halvorson et al. (2000)    | North Dakota, US       | Silt loam | 422            | 12                     | Spring wheat  |
| Aulakh et al. (2012)       | Ludhiana, India        | Loamy sand| 563-695        | 4                      | Soybean       |
| Verhulst et al. (2011)     | El Batán, Mexico       | Clay      | 625            | 12                     | Maize         |
| Halvorson et al. (2002)    | Akron, US              | Silt loam | 419            | 5                      | Winter wheat  |
| Lampurlané et al. (2001)   | Catalonia, Spain       | Loamy    | 440            | 4                      | Barley        |
| Chen et al. (2011)         | Northeast China        | Clay loam | 530            | 6                      | Maize         |
| Gruber et al. (2012)       | Hohenheim, Germany     | Loam     | 715            | 10                     | Winter wheat  |
| Gruber et al. (2012)       | Hohenheim, Germany     | Loam     | 715            | 10                     | Oil seed rape |
| Gruber et al. (2012)       | Hohenheim, Germany     | Loam     | 715            | 10                     | Oats          |
| Vogeler et al. (2009)      | Braunschweig, Germany  | Silty loam| 620            | 8                      | Maize         |

**Studies reporting increased yields under conventional tillage**

| Study Reference            | Location               | Soil Type | Yield (kg ha⁻¹) | Study Year (Apr to Mar) | Crop Type     |
|----------------------------|------------------------|-----------|----------------|-------------------------|---------------|
| Chen et al. (2011)         | Northeast China        | Clay loam | 530            | 6                      | Maize         |
| Gruber et al. (2012)       | Hohenheim, Germany     | Loam     | 715            | 10                     | Winter wheat  |
| Gruber et al. (2012)       | Hohenheim, Germany     | Loam     | 715            | 10                     | Oil seed rape |
| Gruber et al. (2012)       | Hohenheim, Germany     | Loam     | 715            | 10                     | Oats          |
| Vogeler et al. (2009)      | Braunschweig, Germany  | Silty loam| 620            | 8                      | Maize         |
|   | Authors          | Location                  | Soil Type   | Depth (cm) | Water Content (%) | Crop       | Water Deficit (mm) |
|---|------------------|---------------------------|-------------|------------|-------------------|------------|-------------------|
|39 | He et al.        | Gaocheng in Hebei, China  | Silt loam   | 494        | 11                | Summer maize | 9945              | 10727            |
|40 | Carter           | Prince Edward Island, Canada | Loam     | 403        | 8                 | Barley     | 2730              | 2790             |
|41 | Nyborg et al.    | North central Alberta     | Loam       | 547        | 11                | Maize      | 2090              | 3240             |
|42 | Nyborg et al.    | North central Alberta     | Silty clay loam | 452       | 11                | Maize      | 2640              | 3750             |
|43 | Buschiazzo et al.| Buenos Aires, Argentina    | Sandy loam  | 660        | 7                 | Maize      | 5000              | 5200             |
|44 | Buschiazzo et al.| La Pampa, Argentina       | Sandy loam  | 639        | 9                 | Sorghum    | 3960              | 4070             |
|45 | Buschiazzo et al.| La Pampa, Argentina       | Sandy loam  | 639        | 9                 | Wheat      | 1440              | 2340             |
|46 | Buschiazzo et al.| San Luis, Argentina       | Loamy sand  | 591        | 10                | Maize      | 1400              | 2150             |
|47 | Wang et al.      | Shouyang, Shanxi, China   | Sandy loam  | 520        | 15                | Spring maize | 4683              | 4827             |
|49 | Franchini et al. | Paraná, southern Brazil   | Clay        | 1651       | 23                | Maize      | 5751              | 6623             |
|50 | Franchini et al. | Paraná, southern Brazil   | Clay        | 1651       | 23                | Wheat      | 2253              | 2287             |
|51 | Filipovic et al. | North-west Slavonia, Croatia | Silt loam | 817        | 4                 | Maize      | 7540              | 7690             |
| Study | Location | Soil Type | Texture | Depth (cm) | Season | Treatment 1 | Treatment 2 |
|-------|-----------|------------|---------|------------|--------|-------------|-------------|
| Sánchez-Girón et al. | Madrid, Spain | Loam | 430 | Winter | 3024 | 3046 |
| Machado et al. (2007) | Oregon, US | Silty | 398 | Winter | 2180 | 2560 |
| Machado et al. (2007) | Oregon, US | Silty | 398 | Spring | 1640 | 2200 |
| Machado et al. (2007) | Oregon, US | Silty | 398 | Spring | 1700 | 3360 |
| Lafond et al. (1992) | Saskatchewan, Canada | Clay | 534 | Spring | 2548 | 2553 |
| Lyon et al. (1998) | Sidney, US | Silty | 440 | Winter | 2430 | 2620 |
| Aulakh et al. (2012) | Ludhiana, India | Loamy sand | 563-995 | Winter | 3226 | 3283 |
| Wilhelm & Wortmann (2004) | Nebraska, US | Silty clay loam | 708 | Maize | 6200 | 6750 |
| Wilhelm & Wortmann (2004) | Nebraska, US | Silty clay loam | 708 | Soybean | 2450 | 2480 |

Studies reporting little/no difference in yields under both tillage systems

| Study | Location | Soil Type | Texture | Depth (cm) | Season | Treatment | Treatment |
|-------|-----------|------------|---------|------------|--------|-----------|-----------|
| Carter (2005) | Prince Edward Island, Canada | Sandy loam | 403 | 9 | Soybean | 1540 | 1540 |
Table 4. *Soil carbon sequestration rates under zero tillage*

| Region                        | Carbon sequestration rate achievable by reduced tillage (g C/m²/year) | Time period to attain the sequestration rate | Depth of soil (cm) | Reference                |
|-------------------------------|------------------------------------------------------------------------|---------------------------------------------|-------------------|--------------------------|
| Global soils                 | 57                                                                     | 15 years                                    | Top 22 cm         | West & Post (2002)       |
| US Great plains              | 30-60                                                                  | -                                           | -                 | Follet (2001)            |
| US Croplands                 | 10-50                                                                  | In 5-10 years                               | Top 20 cm         | Lal *et al.* (1998)      |
| US Croplands                 | 34                                                                     | 20 years                                    | Top 30 cm         | West & Marland (2002b)   |
| Global soils                 | 33                                                                     | 30 years                                    | Top 30 cm         | Hermle *et al.* (2008)   |
| Tropical-humid               | 3-20                                                                   | 30 years                                    | Top 100 cm        | Farina *et al.* (2011)   |
| Sub tropical humid           | 2.67                                                                   | 10 years                                    | 60 cm             | Sainju *et al.* (2008)   |
| Sub tropical humid           | 0.7                                                                    | 7 years                                     | 40 cm             | Al-Kaisi *et al.* (2005) |
| Semi arid                    | 0.55                                                                   | 20 years                                    | 20 cm             | Hernanz *et al.* (2009)  |
| Environment          | Depth (m) | Duration (years) | Depth of Growth (cm) | Reference                      |
|----------------------|-----------|------------------|----------------------|--------------------------------|
| Semi-arid            | 0.5       | 17               | 60                   | López-Fando & Pardo (2011)     |
| Semi-arid            | 2.46      | 16               | 30                   | Álvaro-Fuentes et al. (2009)   |
| Arid areas in India  | 2.69      | 20               | 30                   | Grace et al. (2012)            |
**Fig. 1.** Net sequestration of carbon (t/ha) under zero tillage in comparison to conventional tillage as affected by duration under zero tillage in tropical and temperate soils. ($F_{1,55} = 1.42$, $NS$ overall, $F_{1,16} = 4.40$, $P < 0.05$ tropical, $F_{1,37} = 0.54$, $NS$ temperate; for the data sets used please refer to Table 2).

**Fig. 2.** Carbon sequestration rate in tropical and temperate soils ($F_{1,55} = 16.57$, $P < 0.001$ overall, $F_{1,16} = 7.03$, $P < 0.05$ tropical, $F_{1,37} = 17.73$, $P < 0.001$ temperate; Please refer to Table 2 for the sources of data used in this figure).

**Fig. 3.** Yield advantage versus years under zero tillage for winter wheat, soybean and maize (Taken from the data in Table 3).
Fig. 1.

Temperate

\[ y = 0.3218x + 4.009 \]

\[ R^2 = 0.05 \]

Tropical

\[ y = 1.0411x - 1.0485 \]

\[ R^2 = 0.23 \]
Fig. 2.

Temperate
\[ y = 0.0166x - 0.2421 \]
\[ R^2 = 0.30 \]

Tropical
\[ y = 0.0354x - 0.0215 \]
\[ R^2 = 0.38 \]
Maize
\[ y = -0.5081x - 8.5045 \]
\[ R^2 = 0.01 \]

Soybean
\[ y = 0.5578x + 2.0978 \]
\[ R^2 = 0.14 \]

Winter wheat
\[ y = -0.7799x + 8.7384 \]
\[ R^2 = 0.06 \]

Fig. 3.