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 (N_2O) 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 N_2O emissions under long-term zero tillage have been reported in the literature but significant variability exists in the N_2O flux information. Long-term,

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location-specific studies are needed urgently to determine the precise role of zero tillage in driving N_2O 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*. 2002*b*; 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*. 2000*a*; 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 (CO_2) (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_2O), a greenhouse gas (GHG) with high global warming potential (Six *et al*. 2002*b*, 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_2O 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 2002*a*) 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.

$$\text{t C per ha} = \frac{\%C \times bulk\ density \times soil\ depth \times 100}{100} \tag{1}$$

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.

$$\text{Relative yield (\%)} = \frac{Yield\ Zero\ Till\ in\ kg/ha}{Yield\ Conventional\ Till\ in\ kg/ha} \times 100 \qquad (2)$$

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*. 2000*b*). 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 mychorrhyzal 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 2007*b*) 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 CO_2 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 2007*b*) with a total increase of 1.9 ppm per year. Apart from CO_2, the atmospheric concentration of CH_4 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 2007*b*). Agriculture can act as both a sink and source for the GHGs of CO_2, CH_4 and N_2O based on the various mitigation strategies adopted. The IPCC (2007*a*) 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 2004*a*) and iii) reduced emissions of CO_2 during decomposition of crop residues triggered by ploughing and reduced use of fossil fuel in farm operations (West & Marland 2002*a*). 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 2004*a*), and increasing C sequestration in soil can mitigate increasing atmospheric CO_2 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 2004*a*). 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 (2002*a*) 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*. (2002*b*) 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 (2004*b*) 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 2004*b*; 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.* (2000*a*) 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.* (2001*b*). 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*. 2002*a*). 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*. (2002*b*) 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*. 2000*a*). 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_2O 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_2O 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_2O. If N_2O 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_2O produced may be consumed within the profile over time. Although most reported N_2O emissions are quantitatively less in comparison to CO_2 emissions, N_2O assumes a greater significance due to its larger global warming potential (296 times that of CO_2: IPCC 2001). Indeed, increased N_2O 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_2O emissions, with lower N_2O 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_2O 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_2O 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_2O flux, especially to investigate the time post conversion at which N_2O 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 CH_4-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 CH_4 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 CH_4 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 N_2O emissions from zero tillage have been reported, crucially some long-term studies have indicated a stabilization of N_2O 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 N_2O 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 (2002*b*) based on comparisons of 76 long-term experiments up to soil depths of 30 cm. After accounting for the CO_2 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 CH_4 taken up in soil, net sequestration was negative with an overall negative greenhouse balance of 214 kg CO_2- equivalents/ha/yr (Six *et al*. 2002*b*). However, Six *et al*. (2002*b*) 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 CO_2- equivalents/m^2/yr) compared to conventional till (114 g CO_2- equivalents /m^2/yr). In most studies it would seem the slightly higher or comparable N_2O 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 CO_2- 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 CO_2- 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-logging 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 N_2O. However, declining N_2O 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 N_2O 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

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 No	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 Benito (2010)	Burgos, Spain	Loamy sand in surface	10	Cereal – fallow, Cereal legume	30	4.6	17.80	Temperate
2	Deen & Kataki (2003)	Ontario, Canada	Silt loam	25	Maize, Soybean	60	36.7	39.0	Temperate
3	López-Fando & Pardo	Toledo, Central Spain	Loamy sand	16	Chick pea, barley	30	26.5	32.6	Temperate

	(2011)								
4	Chatterjee & Lal (2009)	Michigan, US	Clay loam	10	Maize-soybean	60	97.6	104.0	Temperate
5	Chatterjee & Lal (2009)	Ohio, US	Clay loam, silty clay loam	10	Maize-soybean	60	82.3	79.0	Temperate
6	Chatterjee & Lal (2009)	Ohio, US	Loam	15	Maize-soybean	60	117.0	143.0	Temperate
7	Chatterjee & Lal (2009)	Ohio, US	Silt loam	6	Maize-soybean	60	46.3	66.7	Temperate
8	Chatterjee & Lal (2009)	Pennsylvania, US	Loam	30	Maize-alfalfa	60	96.4	83.4	Temperate

9	Puget & Lal (2005)	Ohio, US	Silty clay loam	8	Maize	20	88.5	90.9	Temperate
10	Dolan *et al*. (2006)	Minnesota, US	Silt loam	23	Soybean, maize	40	117.0	106.0	Temperate
11	Kahlon *et al*. (2013)	Ohio, US	Silt loam	22	-	15	21.4	27.6	Temperate
12	Yang *et al*. (2008)	Ontario, Canada	Clay loam	8	Maize, maize-soybean rotation	30	104.8	112.9	Temperate
13	Yang & Wander (1999)	Urbana, US	Silt loam	8	Soybean	30	46.6	58.5	Tropical
14	Lou *et al*. (2012)	Jianping county, China	Sandy loam	12	Maize	100	87.6	93.1	Temperate
15	Lou *et al*.	Changtu	Loam	5	Maize	100	95.4	96.3	Temperate

	(2012)	county, China							
16	Jemai *et al*. (2012)	Mateur, Tunisia	Clay loam	3	Wheat/faba bean rotation	50	83.9	80.2	Temperate
17	Jemai *et al*. (2012)	Mateur, Tunisia	Clay loam	7	Wheat/sulla rotation	50	83.9	73.1	Temperate
18	Lal (1997)	Ibadan, Nigeria	Sandy	8	Maize	10	2.0	2.4	Tropical
19	Larney *et al*. (1997)	Alberta, Canada	Sandy clay loam to clay loam	7	Spring wheat - fallow	15	27.1	29.2	Temperate
20	Larney *et al*. (1997)	Alberta, Canada	Sandy clay loam to clay loam	7	Continuous spring wheat	15	31.0	33.0	Temperate
21	Sisti *et al*. (2004)	Passo Fundo, Brazil	Clay	13	Wheat-soybean rotation	30	60.7	65.0	Tropical

22	Metay *et al*. (2007)	Cerrados, Brazil	Clay	5	Leguminous cover crops	10	19.9	22.3	Tropical
23	Dendooven *et al*. (2012)	Central Mexico	Clay	19	Wheat and maize	60	76.8	117.7	Tropical
24	Varvel & Wilhelm (2011)	Lincoln, US	Silty clay loam	20	Maize, soybean	60	90.5	114.4	Temperate
25	Varvel & Wilhelm (2011)	Lincoln, US	Silty clay loam	20	Maize, soybean	90	104.8	138.6	Temperate
26	Varvel & Wilhelm (2011)	Lincoln, US	Silty clay loam	20	Maize, soybean	120	123.3	165.4	Temperate
27	Dalal *et al*. (2011)	Queensland, Australia	Clay	40	Wheat, barley	10	19.8	20.2	Temperate

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

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 Federal, 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

					wheat			
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,	Clay loam	10	Wheat, barley,	18	47.3	51.8	Temperate

	Siri-Prieto (2009)	Uruguay			and oat for winter crops and maize, sunflower, sorghum, and soybean for summer crops				
44	Mrabet *et al*. (2001*a*)	Sidi El Aydi, Morocco	Clay	11	Wheat- maize, lentils fallow	20	33.9	37.3	Temperate
45	Abreu *et al*. (2011)	Oklahoma, US	Silt loam	5	Soybean–maize–wheat–soybean–maize	110	101.6	119.2	Temperate
46	Abreu *et al*. (2011)	Oklahoma, US	Silt loam	7	Wheat–soybean–maize	110	111.6	127.4	Temperate
47	Abreu *et*	Oklahoma,	Silt loam	5	Maize–wheat	110	104.5	116.3	Temperate

	al. (2011)	US							
48	Abreu *et al*. (2011)	Oklahoma, US	Silt loam	12	Wheat/soybean/ grain sorghum	110	72.1	81.9	Temperate
49	Zanatta *et al*. (2007)	Rio Grande do Sul State, Brazil.	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)
			Studies reporting increased yields under zero till					
1	Chen *et al*. (2011)	Northeast China	Clay loam	530	6	Soybean	2659	2441
2	Su *et al*. (2007)	Henan Province, China	Loam	614	6	Winter wheat	4679	4125
3	Hemmat & Eskandari (2006)	East Azerbaijan Province, Iran	Clay loam	375	3	Winter wheat	1435	1014
4	Vogeler *et al*. (2009)	Braunschweig, Germany	Silty loam	620	8	Winter wheat	5790	5680
5	Vogeler *et al*. (2009)	Braunschweig, Germany	Silty loam	620	8	Field beans	2910	2520
6	He *et al*. (2011)	Gaocheng in Hebei, China	Silt loam	494	11	Winter wheat	6154	5945
7	Morell *et al*. (2011)	Agramunt , Spain	Sandy silt loam	435	10	Winter barley	1590	1148

8	Ekeberg & Riley (1997)	Southeast Norway	Loam	415	9	Spring barley	4310	4020
9	Ekeberg & Riley (1997)	Southeast Norway	Loam	415	9	Spring wheat	3760	3280
10	Cantero-Martínez *et al*. (2003)	Guissona, Spain	Clay loam	<350	3	Barley	4163	3803
11	Cantero-Martínez *et al*. (2003)	Agramunt, Spain	Sandy silt loam	<350	3	Barley	3770	3230
12	Buschiazzo *et al*. (1998)	Córdoba, Argentina	Silt loam	760	11	Soybean	3230	2480
13	Buschiazzo *et al*. (1998)	Córdoba, Argentina	Silt loam	760	11	Sorghum	5720	4780
14	Buschiazzo *et al*. (1998)	Buenos Aire, Argentina	Sandy loam	660	7	Wheat	1600	1040
15	Mrabet (2000)	Casablanca, Morocco	Clay	296	3	Maize	2470	2410
16	Wang *et al*. (2012)	Luoyang, Henan, China	Sandy loam	570	6	Winter wheat	4534	4413
17	Franchini *et al*. (2012)	Paraná, southern Brazil	Clay	1651	23	Soybean	3071	2496

18	Kutcher & Malhi (2010)	Saskatchewan, Canada	Sandy loam	-	5	Barley	3069	2796
19	Kutcher & Malhi (2010)	Saskatchewan, Canada	Clay loam	-	5	Barley	3133	2760
20	Arshad *et al.* (1994)	Alta, Canada	Clay	449	3	Wheat	1570	1530
21	Filipovic *et al.* (2006)	north-west Slavonia, Croatia	Silt loam	817	4	Winter wheat	5680	5590
22	Wang *et al.* (2011)	Shanxi province, China	Sandy loam	520	5	Maize	5347	5185
23	Karunatilake *et al.* (2000)	Willsboro, New York	Clay loam	-	7	Maize	7260	6420
24	Sánchez-Girón *et al.* (2004)	Madrid, Spain	Loam	430	13	Winter wheat	3169	3032
25	Kumar *et al.* (2013)	western Uttar Pradesh, India	Sandy loam	800	3	Winter wheat	4490	4090
26	Lafond *et al.* (1992)	Saskatchewan, Canada	Clay	534	3	Winter wheat	2070	2039

27	Hemmat & Eskandari (2004)	Maragheh, Iran	Clay	476	2	Winter wheat	1717	1301
28	Halvorson *et al*. (2000)	North Dakota, US	Silt loam	422	12	Spring wheat	1881	1830
29	Aulakh *et al*. (2012)	Ludhiana, India	Loamy sand	563-995	4	Soybean	2226	2178
30	Verhulst *et al*. (2011)	El Batán, Mexico	Clay	625	12	Maize	5650	4310
31	Halvorson *et al*. (2002)	Akron, US	Silt loam	419	5	Winter wheat	3122	2975
32	Lampurlanés *et al*. (2001)	Catalonia, Spain	Loamy	440	4	Barley	3608	3371
Studies reporting increased yields under conventional tillage								
33	Chen *et al*. (2011)	Northeast China	Clay loam	530	6	Maize	4860	6787
34	Gruber *et al*. (2012)	Hohenheim, Germany	Loam	715	10	Winter wheat	8100	8400
35	Gruber *et al*. (2012)	Hohenheim, Germany	Loam	715	10	Oil seed rape	4000	4100
36	Gruber *et al*. (2012)	Hohenheim, Germany	Loam	715	10	Oats	3800	4700
38	Vogeler *et al*. (2009)	Braunschweig, Germany	Silty loam	620	8	Maize	4780	5390

39	He *et al.* (2011)	Gaocheng in Hebei, China	Silt loam	494	11	Summer maize	9945	10727
40	Carter (2005)	Prince Edward Island, Canada	Loam	403	8	Barley	2730	2790
41	Nyborg *et al.* (1995)	North central Alberta	Loam	547	11	Maize	2090	3240
42	Nyborg *et al.* (1995)	North central Alberta	Silty clay loam	452	11	Maize	2640	3750
43	Buschiazzo *et al.* (1998)	Buenos Aire, Argentina	Sandy loam	660	7	Maize	5000	5200
44	Buschiazzo *et al.* (1998)	La Pampa, Argentina	Sandy loam	639	9	Sorghum	3960	4070
45	Buschiazzo *et al.* (1998)	La Pampa, Argentina	Sandy loam	639	9	Wheat	1440	2340
46	Buschiazzo *et al.* (1998)	San Luis, Argentina	Loamy sand	591	10	Maize	1400	2150
47	Wang *et al.* (2012)	Shouyang, Shanxi, China	Sandy loam	520	15	Spring maize	4683	4827
49	Franchini *et al.* (2012)	Paraná, southern Brazil	Clay	1651	23	Maize	5751	6623
50	Franchini *et al.* (2012)	Paraná, southern Brazil	Clay	1651	23	Wheat	2253	2287
51	Filipovic *et al.* (2006)	north-west Slavonia, Croatia	Silt loam	817	4	Maize	7540	7690

52	Sánchez-Girón *et al*. (2004)	Madrid, Spain	Loam	430	16	Winter barley	3024	3046
53	Machado *et al*. (2007)	Oregon, US	Silty	398	6	Winter wheat	2180	2560
54	Machado *et al*. (2007)	Oregon, US	Silty	398	6	Spring wheat	1640	2200
55	Machado *et al*. (2007)	Oregon, US	Silty	398	6	Spring barley	1700	3360
56	Lafond *et al*. (1992)	Saskatchewan, Canada	Clay	534	3	Spring wheat	2548	2553
57	Lyon *et al*. (1998)	Sidney, US	Silty	440	25	Winter wheat	2430	2620
58	Aulakh *et al*. (2012)	Ludhiana, India	Loamy sand	563-995	4	Winter wheat	3226	3283
59	Wilhelm & Wortmann (2004)	Nebraska, US	Silty clay loam	708	16	Maize	6200	6750
60	Wilhelm & Wortmann (2004)	Nebraska, US	Silty clay loam	708	16	Soybean	2450	2480
Studies reporting little/no difference in yields under both tillage systems								
61	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 $C/m^2/year$)	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 (2002*b*)
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)

Semi arid	0.5	17 years	60 cm	López-Fando & Pardo (2011)
Semi arid	2.46	16 years	30 cm	Álvaro-Fuentes *et al*. (2009)
Arid areas in India	2.69	20 years	30 cm	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).

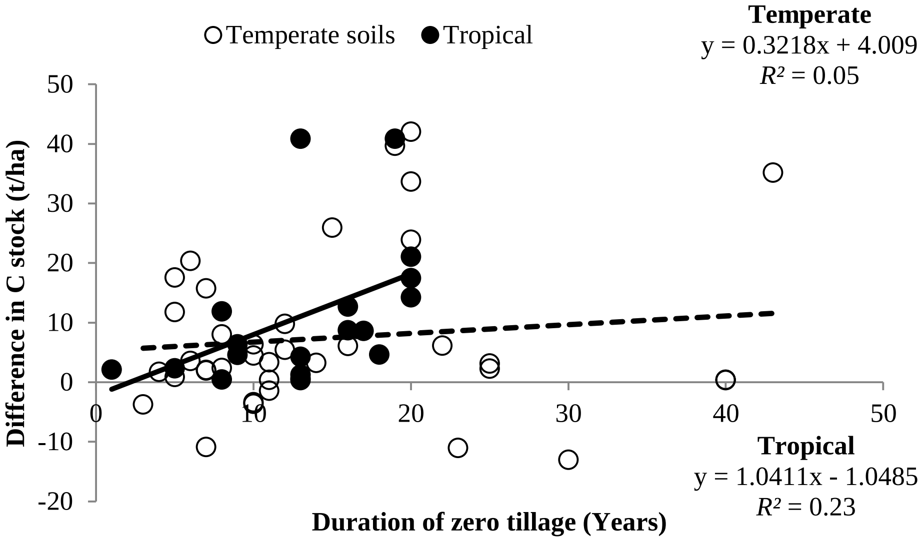
○Temperate soils
●Tropical
Temperate
y = 0.3218x + 4.009
$R^2 = 0.05$
Tropical
y = 1.0411x - 1.0485
$R^2 = 0.23$
Difference in C stock (t/ha)
50
40
30
20
10
0
-10
-20
0
10
20
30
40
50
Duration of zero tillage (Years)

Fig. 1.

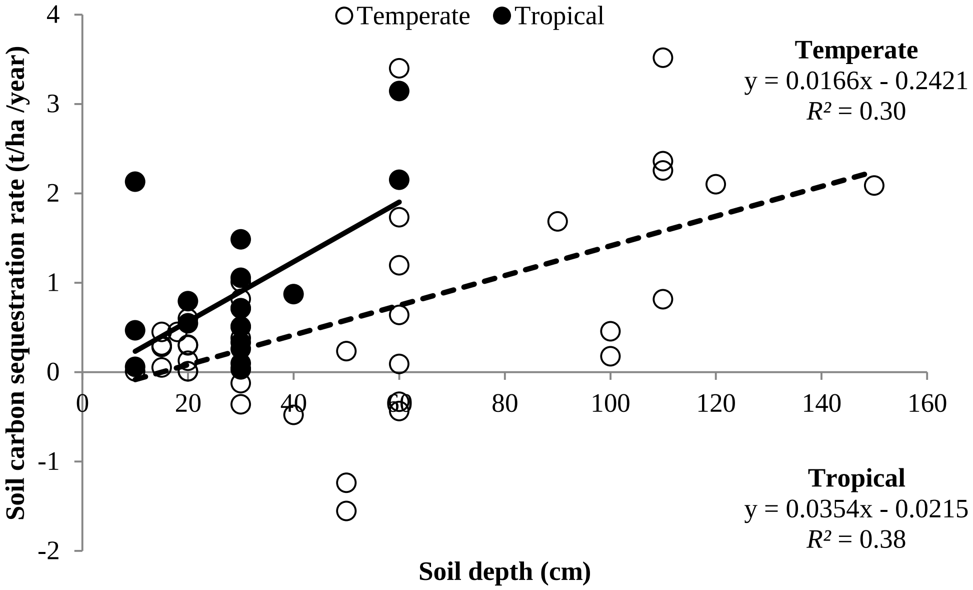
○Temperate ●Tropical
Temperate
y = 0.0166x - 0.2421
R² = 0.30
Tropical
y = 0.0354x - 0.0215
R² = 0.38
Soil carbon sequestration rate (t/ha /year)
Soil depth (cm)
4
3
2
1
0
-1
-2
0
20
40
60
80
100
120
140
160

Fig. 2.

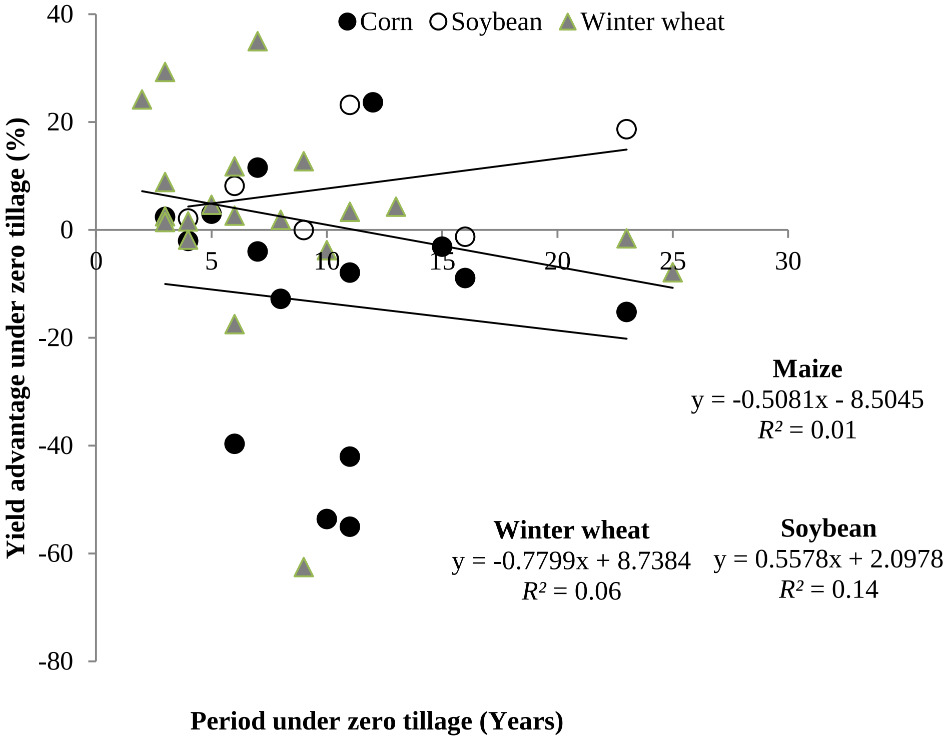
40
20
0
-20
-40
-60
-80
0
5
10
15
20
25
30
● Corn
○ Soybean
▲ Winter wheat
Yield advantage under zero tillage (%)
Period under zero tillage (Years)
Maize
y = -0.5081x - 8.5045
R² = 0.01
Winter wheat
y = -0.7799x + 8.7384
R² = 0.06
Soybean
y = 0.5578x + 2.0978
R² = 0.14

Fig. 3.