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Conservation agriculture and ecosystem services: An overview

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ABSTRACT

Conservation agriculture (CA) changes soil properties and processes compared to conventional agriculture. These changes can, in turn, affect the delivery of ecosystem services, including climate regulation through carbon sequestration and greenhouse gas emissions, and regulation and provision of water through soil physical, chemical and biological properties. Conservation agriculture can also affect the underlying biodiversity that supports many ecosystem services. In this overview, we summarize the current status of the science, the gaps in understanding, and highlight some research priorities for ecosystem services in conservational agriculture. The review is based on global literature but also addresses the potential and limitations of conservation agriculture for low productivity, smallholder farming systems, particularly in Sub Saharan Africa and South Asia. There is clear evidence that topsoil organic matter increases with conservation agriculture and with it other soil properties and processes that reduce erosion and runoff and increase water quality. The impacts on other ecosystem services are less clear. Only about half the 100+ studies comparing soil carbon sequestration with no-till and conventional tillage indicated increased sequestration with no till; this is despite continued claims that conservation agriculture sequesters soil carbon. The same can be said for other ecosystem services. Some studies report higher greenhouse gas emissions (nitrous oxide and methane) with conservation agriculture compared to conventional, while others find lower emissions. Soil moisture retention can be higher with conservation agriculture, resulting in higher and more stable yields during dry seasons but the amounts of residues and soil organic matter levels required to attain higher soil moisture content is not known. Biodiversity is higher in CA compared to conventional practices. In general, this higher diversity can be related to increased ecosystem services such as pest control or pollination but strong evidence of cause and effect or good estimates of magnitude of impact are few and these effects are not consistent. The delivery of ecosystem services with conservation agriculture will vary with the climate, soils and crop rotations but there is insufficient information to support a predictive understanding of where conservation agriculture results in better delivery of ecosystem services compared to conventional practices. Establishing a set of strategically located experimental sites that compare CA with conventional agriculture on a range of soil-climate types would facilitate establishing a predictive understanding of the relative controls of different factors (soil, climate, and management) on ES outcomes, and ultimately in assessing the feasibility of CA or CA practices in different sites and socioeconomic situations.

The feasibility of conservation agriculture for recuperating degraded soils and increasing crop yields on low productivity, smallholder farming systems in the tropics and subtropics is discussed. It is clear that the biggest obstacle to improving soils and other ES through conservation agriculture in these situations is the lack of residues produced and the competition for alternate, higher value use of residues. This limitation, as well as others, point to a phased approach to promoting conservation agriculture in these regions and careful consideration of the feasibility of conservation agriculture based on evidence in different agroecological and socioeconomic conditions.

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1. Introduction

Provision of food is a primary function and key ecosystem service (ES) of agriculture. There is growing recognition that agricultural systems are both dependent on ES that support production functions and a source of important agricultural and non-agricultural ES. Ecosystem services are categorized as provisioning, regulating, supporting, and cultural. The level of delivery of the different services is determined by a combination of ecosystem properties, including soils, vegetation, and climate and the resulting ecological processes (Fisher et al., 2009). Agricultural intensification aimed at increasing production can affect ecosystem components and processes. Intensification can disrupt many of the regulating and supporting ES, including nutrient cycling, climate regulation, regulation of water quality and quantity, pollination services, and pest control (Fig. 1; Power, 2010). It can also alter the biological diversity underpinning many of these ES. While some agricultural practices can decrease ES delivery (tradeoffs) others can enhance or maintain ES (synergies). Increasing food production at the expense of ESs can undermine agroecosystem sustainability including crop production.

Conservation agriculture (CA) is a system of agronomic practices that include reduced tillage (RT) or no-till (NT), permanent organic soil cover by retaining crop residues, and crop rotations, including cover crops. Together these practices aim to increase crop yields by enhancing several regulating and supporting ESs. Though CA was originally introduced to regulate wind and water erosion (Baveye et al., 2011), it is now considered to deliver multiple ES. This paper focuses on the effects of CA on selected ES such as climate regulation as related to soil carbon sequestration and greenhouse gas emissions and the provision and regulation of water and nutrients through modification of several soil properties and processes. The role of biodiversity, particularly soil functional diversity is also discussed, where possible. Pest and disease control and pollination are briefly mentioned. These ES were selected because they are the ones most likely affected by CA practices.

Conservation agriculture was originally designed as a response to the US Dust Bowl (Baveye et al., 2011). Since then, the adoption of CA has been rapid, particularly in North America, South America, and Australia (Derpsch and Theodor, 2009). It is primarily practiced on large-scale, mechanized farms, and requires large applications of herbicides to control weeds that are normally controlled by tillage. There are now concerted efforts that are promoting CA in smallholder systems in South Asia (Hobbs et al., 2008) and Sub Saharan Africa (Valbuena et al., 2012). Whether CA, which was designed in high-input systems in more temperate regions, can work and deliver ES in smallholder systems of the tropics and subtropics is unclear and warrants further consideration based on the evidence to date.

Over the past ten years numerous research papers and reviews have looked at the extent to which ES are generated through CA compared to conventional practices. Much of that research has focused on effects of RT and NT compared with conventional tillage (CT) where the effects of residue management and crop rotations are often confounded with tillage. Previous reviews indicate that CA can reduce water and wind erosion due to protection of the soil surface with residue retention and increased water infiltration and decreased runoff with NT (Verhulst et al., 2010). Benefits of CA on other ES including nutrient cycling, carbon sequestration, and pest and disease control are quite variable, from positive, to neutral or even negative depending on site-specific context, management, soil type, and climate.

This paper summarizes the state-of-knowledge of CA and ES and highlights the gaps and questions needed to provide a more predictive framework for ES delivered through CA. The summaries are based on the global literature including the growing literature on CA from smallholder farming systems, particularly Sub Saharan Africa and South Asia. The types of experiments installed for testing CA and comparing with conventional practices (tillage, residue removal or incorporation and monocultures) do not necessarily have the design required to separate the individual and combined effects of the different CA practices on ES. Comparisons often come from experiments that include one or two of the practices, with comparisons of tillage practices with residues being the most common. The approach we used examines each ES and how CA practices influence soil and plant processes and ES outcomes as described in Palm et al. (2007). We also discuss how ES relates to crop productivity, with an emphasis on situations where increasing regulating and supporting ESs do not compromise, but instead bolster, production functions.

2. Climate Regulation

The ES of climate regulation refers to processes that contribute to or mitigate the build-up of greenhouse gases (GHG) in the atmosphere or other factors, such as albedo, that contribute to global climate forcing (Millennium Ecosystem Assessment, 2005). The net potential of CA to contribute to climate regulation and serve as a global warming mitigation strategy depends on the direction and magnitude of changes in soil C, nitrous oxide (N_2O) and methane (CH_4) emissions associated with its implementation compared to conventional practices. Collectively this is assessed in terms of the global warming potential of the farming practices which are soil, climate and management dependent (Robertson and Grace, 2004). For example, if there is an increase in soil C that is greater than the combined increase in N_2O or CH_4 emissions (expressed as CO_2 equivalents), the net global warming potential decreases.

2.1. Soil carbon sequestration

Soil C sequestration refers to the increase in C stored in the soil by capturing atmospheric CO_2 as a result of changes in land use or management (Powlson et al., 2011b; West and Post, 2002). While CA was not initially conceived as a practice to sequester soil C, it is now considered as a potential technology to mitigate greenhouse gas emissions and has become a focus of CA research. Several reviews summarize the effects of the different component practices of CA on soil C stocks compared to conventional practices (Branca et al., 2011; Corsi et al., 2012; Gattinger et al., 2011; Govaerts et al., 2009; Grace et al., 2012; Lal, 2011; Luo et al., 2010; Ogle et al., 2012; Ogle et al., 2005; Six et al., 2002; West and Post, 2002). Though most studies report changes in soil C stocks or storage, an increase in soil C stocks does not necessarily represent sequestration or climate mitigation potential if there is not a net transfer of CO_2 from the atmosphere. As discussed by Powlson et al. (2011b), such situations relevant to CA are if residue retention results in increased C storage in the CA field but a reduction in soil C where the residue had been sourced. These factors are not usually considered in CA studies. In addition, some consider soil C sequestration as that C which is held in the more recalcitrant or protected forms and thus less susceptible to losses from decomposition (Powlson et al., 2011b; West and Post, 2002). Most studies however just report on the changes in the total C stored and not the changes in the recalcitrant fractions. As such we will refer to the changes in soil C reported in the studies to indicate the *potential* for CA to serve as a net sink of atmospheric CO_2.

2.1.1. Factors and processes affecting soil carbon sequestration

Simply put, soil C content is the balance between the C inputs and decomposition. Understanding and quantifying the factors and processes that determine C inputs and decomposition, however, is not simple but necessary to build the scientific evidence needed to

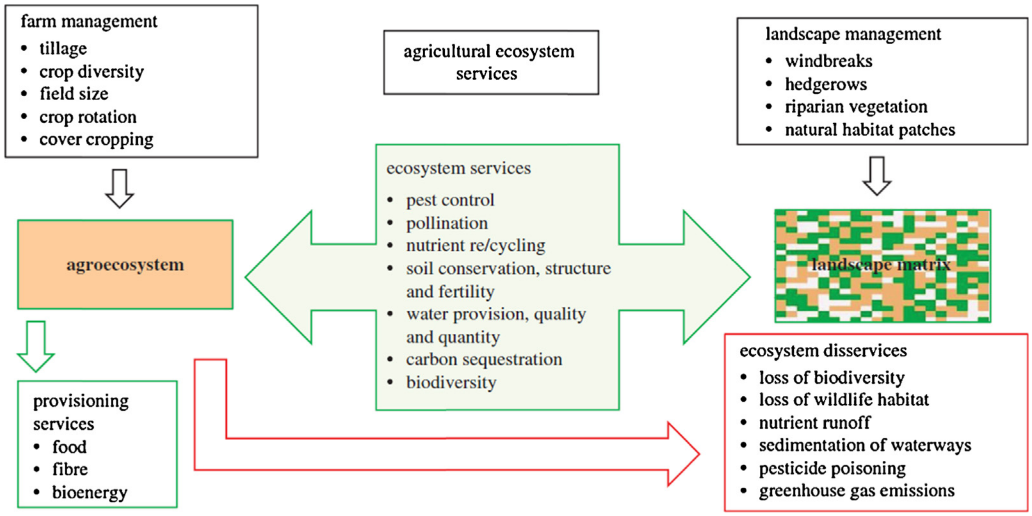

Fig. 1. Diagram showing the potential ecosystem services in agricultural ecosystems and how they can be modified by different agricultural management practices and landscape structure. (from Power, 2010).

manage soil C. The abiotic and biological factors, soil and plant processes, and management practices influencing soil C formation and decomposition are reviewed by Giller et al. (2009), Govaerts et al. (2009), Powlson et al. (2011a), and others. Factors that increase biomass production and C inputs will increase soil C, as long as decomposition rates do not increase similarly. Climate (rainfall and temperature), soil type (texture and mineralogy), and nutrient and water availability are the primary determinants of biomass production and decomposition rates. The CA practices of crop rotations and surface residue retention are intended to increase C inputs relative to conventional practices and NT to decrease decomposition through increased soil aggregation and a protection of soil C from decomposers. The balance of those two processes and the resulting soil C will vary with soil, climate and other management practices.

The potential changes in soil C are larger in tropical moist climates followed by tropical dry, temperate moist, and temperate dry climates (Ogle et al., 2005). Several of the studies which show lower soil C with NT than with CT attribute the lower soil C to cooler and wetter climates. The lower soil C is related to reduced crop yields and C inputs caused by lower soil temperatures under surface residue retention compared with CT systems (Ogle et al., 2012).

The effects of nutrient and water availability on crop production, C inputs and decomposition can be managed through fertilization (mineral or organic inputs), weed and pest control, irrigation, crop rotations and intensification, tillage practices, and residue management. Nitrogen (N) fertilizer applications increase crop yields and the C inputs to soils but may increase rates of decomposition of C inputs and soil C (Chivenge et al., 2011). The net effect on changes in soil C storage depends on the balance between these processes. Studies have generally shown that applications of fertilizer N are associated with increased levels of soil C compared to no application of N (Powlson et al., 2011b; Ladha et al., 2011). A study by Ghimire et al. (2012) though did not show an effect of N fertilization. The amount of residues added in this study was limited to 4 Mg ha^{-1}, which may be insufficient level of inputs to shift the balance to net soil C storage in this subtropical environment with high rates of decomposition. Higher soil C with certain crop rotations has also been attributed to a positive N balance either through N-fixing legumes or N fertilization (Corsi et al., 2012). A need exists for a better process-level understanding of differential effect of N, P, and S fertilization on the direction and magnitude of changes in soil C storage (Lal, 2011).

The potential for storing soil C may decrease in water limited-regions due to differences in the balance of C inputs and decomposition (Blanco-Canqui et al., 2011); this potential can be increased through water management. While rainfall, temperature and management determine the balance between production and decomposition, soil properties determine the level of C sequestration for a given climate. The primary soil factors are texture, mineralogy, soil structure (aggregation) and depth. There are limits to the amount of C that soils can sequester; this soil C saturation potential is determined by soil texture (fine silt + clay), physical protection, and perhaps the biochemical composition of the organic inputs (Hassink, 1996, Six et al., 2002). Soils with a large C saturation deficit will sequester more C than those close to saturation.

2.1.2. Soil C sequestration and conservation agriculture - summary of findings

Tillage: Reduced-tillage or NT as a CA component may increase soil C compared with CT but these increases are often confined to near-surface layers (<10 cm). At deeper depths, soil C in CA may be equal or even lower compared with CT. The potential of CA for storing C is not conclusive. It depends on antecedent soil C concentration, cropping system, management duration, soil texture and slope, climate (Appendix A; Govaerts et al., 2009; Luo et al., 2010). More data are available from temperate (i.e., USA) than from tropical regions. Across 100 comparisons, soil C stock in NT was lower in 7 cases, higher in 54 cases and equal in 39 cases compared with CT in the 0- to 30-cm soil depth after 5 years or more of NT implementation (Appendix A; Govaerts et al., 2009). These studies were primarily from USA and Canada and some from Brazil, Mexico, Spain, Switzerland, Australia, and China. A meta-analysis found increased soil C in the topsoil (0-10 cm) on conversion of CT to NT but no significant difference over the soil profile to 40 cm due to a redistribution of C in the profile (Luo et al., 2010).

A problem with the summary findings is that a majority of studies published prior to 2009 reported soil C on a fixed depth basis rather than equivalent soil mass basis which can overestimate soil C sequestration for the treatment with higher bulk density, which is usually the NT treatment. This is discussed in more detail at the end of this section.

Crop rotations: Crop rotations have less effect on soil C than tillage (West and Post, 2002). Crop rotations can affect soil C by increased biomass production and C inputs from the different crops in the system or through altering pest cycles, diversifying rooting patterns and rooting depth. Experimental designs have confounded crop rotations with tillage making it difficult to make conclusions about the effects of rotations alone. Crop rotations effects on soil C are often mixed (Corsi et al., 2012). High-residue producing crops may sequester more C than crops with low residue input. Intensification of cropping systems such as increased number of crops per year, double cropping, and addition of cover crops can result in increased soil C storage under NT (West and Post, 2002; Luo et al., 2010). West and Post (2002) found interactions with crop rotations and tillage practice; in general, crop rotations sequestered more C than monocultures on conversion to NT, though there were notable exceptions with corn-soybean rotations with less soil C than monoculture maize.

It is generally recognized that the differential effects of rotations on soil C are simply related to the amounts of above and below ground biomass (residues and roots) produced and retained in the system (West and Post, 2002). Unfortunately, few studies have measured or reported the residue inputs, particularly root biomass or rooting patterns, to better explain rotation effects. In Brazil, Boddey et al. (2010) attributed higher soil C storage in NT than CT to the inclusion of legume intercrops or cover crops in the rotations, and not due simply to higher production and residue inputs. They indicated slower decomposition of residues and lower mineral N in NT compared to CT result in higher root:shoot ratios and belowground C input with NT (Boddey et al., 2010).

Residue retention: Retention of crop residues is an essential component of CA for increasing or maintaining soil C. Factors that increase crop yields will increase the amount of residue available and potentially soil C storage. Fertility management may be the single most important factor to increase residue production and ultimately increase soil C storage, whether the system is NT or CT or incorporates crop rotations (Giller et al., 2009). This will be important for increasing C inputs and soil C in low input-low productivity systems found in much of Sub Saharan Africa and parts of South Asia (Paul et al., 2013; Thierfelder et al., 2013b; Dube et al., 2012; Ghimire et al., 2012; Hillier et al., 2012). As a rough comparison using average regional yields (Hazell and Wood, 2008) and a harvest index of 50% for maize, farms in the US generate 10 Mg ha^{-1} of maize residue while 3 and 1-2 Mg ha^{-1} are produced in South Asia and Sub Saharan Africa, respectively. A study by Paul et al. (2013) in Kenya illustrates the point that limited amounts of residue input may have little or no effects on increasing soil C. They found no differences in soil C concentration between CT and RT when both tillage systems received 4 Mg ha^{-1} of residue for six years. A similar lack of response to 4 Mg ha^{-1} of residue after four years of application was also seen in a subtropical area of Nepal (Ghimire et al., 2012).

Soil C storage is affected more by quantity than by the type or quality of organic inputs. The quality of the residues is determined primarily by the C:N ratio and can be modified by the amounts of lignin and polyphenolics in the material (Palm and Sanchez, 1991). Quality may affect short-term soil C storage and dynamics but does not seem to influence the longer-term C stabilization and storage in the soil (Chivenge et al., 2011; Gentile et al., 2011). The quality of the residues may, however, affect soil fertility and thus the amount of residues produced for C inputs. For example, materials with high C:N, characteristic of cereal crop residues, reduce the available N in the soil due to N immobilization and could result in lower crop production, while residues with high N contents and low C:N ratios, as is the case with many legume residues and legume cover crops, increase soil N availability and possibly crop production (Powlson et al., 2011b; Palm et al., 2001).

The amount of crop residue retained after harvest, either on the soil surface or incorporated, is a key component to CA performance. Unlike most temperate zone agriculture and other large scale farming systems, where NT or RT results in high production and retention of crop residues, residue produced in many small scale farms in Sub Saharan Africa, parts of Latin America and South Asia is not only low but also has many competing uses (Erenstein, 2002). The fate of residues depends on many factors including human and livestock population density, production potential of an area, and fodder markets, (Magnan et al., 2012; Valbuena et al., 2012; Tittonel et al., 2007). The majority of smallholders are mixed crop-livestock farmers who use most crop residues as fodder for livestock. In some areas crop residues are simply burned to clear agricultural fields (Ghimire et al., 2012), while, in other areas, residues are removed from fields by termites (Giller et al., 2009).

Tillage, Crop Rotation, and Residue Retention Interactions: Previous literature on soil C stocks has often discussed effects of tillage, rotations, and residue management separately. It is important to recognize that these CA components interact. For example, the types of crops, intensity of cropping, and duration of the cropping systems determine the amount of inputs and thus the ability of CA to store more C than CT (Appendix A; Govaerts et al., 2009; Luo et al., 2010). Intensification of cropping systems with high above and belowground biomass (i.e, deep-rooted plant species) input may enhance CA systems for storing soil C relative to CT (Luo et al., 2010). Moreover, CA practices such as NT may not store more soil C than CT if they leave limited amount of residues. While it is clear that increasing amount of residues is essential for increasing soil C storage, interaction of residues with soil texture and soil microclimate (moisture and temperature) will ultimately determine rates of residue decomposition and soil C turnover and storage. These multiple and complex interactions that ultimately determine soil C storage make it difficult to identify clear patterns and trends needed for developing practical guidelines.

Models can be useful in evaluating the contribution of different practices and processes to soil C storage. Models can simulate how the interaction among different levels of residue retention, fertility levels, soil temperature and other factors can affect crop yields, residue decomposition rates, and soil C storage under CA (Probert, 2007; Ogle et al., 2012). Several simulation studies (Leite et al., 2004, 2009; Apezteguía et al., 2009) have confirmed relatively small gains in soil under NT due to enhanced sequestration in the slow soil organic matter pool (Chang et al., 2013) Farage et al. (2007), while using CENTURY and RothC for estimating soil C changes with tillage practices, found a small increase in soil C with conversion to NT on sandy soils of West Africa. Ogle et al. (2012) used CENTURY to look at the effects of temperature on crop yields and decomposition rates in the US. They estimated that decreased soil C due to lower crop production with NT under cool temperatures were offset by lower decomposition rates; once the C inputs were reduced by more than 15%, however, there was a decrease in soil C. These modeling exercises can be used to look for these types of threshold effects and interactions among the CA practices in determining the primary factors affecting soil C storage in different environments. Care must be taken to assure that these models are first validated for the soil, climate and crops of interest and that they adequately reflect changes in soil C due to different management practices, especially tillage and residue placement.

2.1.3. Methods for assessing soil carbon stocks

Given the current attention to the potential of agricultural practices to climate change mitigation through soil C sequestration, it is of utmost importance that C stocks are estimated correctly. Differences in methods used for measuring and comparing soil C storage among management practices can lead to different results. This is particularly true when bulk density (the mass of soil per unit volume; g cm^{-3}) and soil profile distribution of C between CT and NT differ (Blanco-Canqui and Lal, 2008; Kettler et al., 2000; Table 1, Appendix A). Tillage results in fairly uniform soil C concentration (g C kg $soil^{-1}$) throughout the plow layer while NT results in a C

Table 1
Bulk density, cumulative soil mass, soil C concentration, cumulative soil C by depth for conventional till and no till treatments. a. Plaza-Bonilla et al. (2010), b. Du et al. (2010). ESM C = the equivalent soil mass C.

A.

Depth cm	Bulk density Tillage g cm^{-3}	Bulk density No Tillage g cm^{-3}	Cumulative soil mass: Tillage Mg ha^{-1}	Cumulative soil mass No Tillage Mg ha^{-1}	Soil C concentration Tillage g kg^{-1}	Soil C concentration No Tillage g kg^{-1}	Cumulative C mass Tillage Mg ha^{-1}	Cumulative C mass No Tillage Mg ha^{-1}
5	1.34	1.29	705	655	6.3	12.9	4.4	8.4
10	1.33	1.45	1,410	1,420	6.3	7.9	8.9	14.5
20	1.33	1.44	2,790	2,950	5.9	5.4	17.0	22.8
30	1.32	1.47	4,160	4,500	6.1	4.3	25.4	29.4
40	1.33	1.42	5,640	5,990	5.7	3.6	33.8	34.8
ESM C							27.4	29.4

B.

Depth cm	Bulk density Tillage g cm^{-3}	Bulk density No Tillage g cm^{-3}	Cumulative soil mass Tillage Mg ha^{-1}	Cumulative soil mass No Tillage Mg ha^{-1}	Soil C concentration Tillage g kg^{-1}	Soil C concentration No Tillage g kg^{-1}	Cumulative C mass Tillage Mg ha^{-1}	Cumulative C mass No Tillage Mg ha^{-1}
5	1.3	1.4	650	700	11.8	14	7.7	9.8
10	1.42	1.52	1,360	1,460	11.2	12	15.6	18.9
20	1.51	1.61	2,870	3,070	11	9.1	32.2	33.6
30	1.6	1.62	4,470	4,690	7.5	7	44.2	44.9
40	1.6	1.58	6,070	6,270	4	3.9	50.6	51.1
ESM C							45.5	44.9

concentration gradient with the highest C concentrations in the topmost layers. Most studies show lower bulk density in the plow layer of CT compared to NT (Appendix A). These differences in soil C concentrations and bulk density between NT and CT can affect estimates of soil C stocks and thus require methods that account for these differences to make valid comparisons.

Methods for reporting soil C data have changed over time, initially with soil C reported simply in terms of % C or g C/kg in different soil depths. The advent of C sequestration research in the late 1980's required the calculation of soil C stocks on an area or volume basis, Mg C ha^{-1}. Most C stocks were computed on a fixed depth basis, which consisted of multiplying C concentration by bulk density, area, and depth. Soil C reported on a fixed depth basis, however, can lead to incorrect conclusions when soil bulk densities differ among the management practices for the same depth interval. Ellert and Bettany (1995) illustrated the importance of reporting soil C on an equivalent soil mass (ESM) basis, rather than fixed soil depth (Fig. 2). There is now general agreement that soil C stocks should be compared using ESM but many studies still do not use it because of methodological difficulties. The result of using fixed depth rather than ESM is that reports of changes in soil C stocks are confounded by management-induced changes in bulk density rather than outright changes in stock.

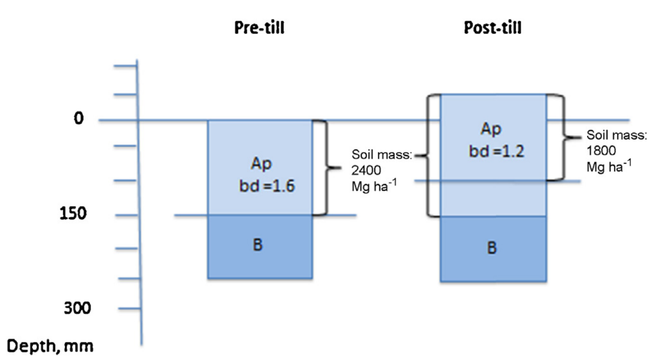

Fig. 2. Illustration showing the differences between sampling a soil that is tilled or not tilled to a fixed depth or an equivalent soil mass basis (from Ellert and Bettany, 1995).

To illustrate this point, we compared soil C sequestration in CT and NT systems by the fixed depth and ESM methods for a 17 year study of a wheat-barley rotation in Spain (Table 1a; Plaza-Bonilla et al., 2010). The fixed depth method indicates that NT stored 4 Mg C ha^{-1} more than CT to a depth of 30 cm. If the ESM method is used, an additional 2.3 cm of soil (340 Mg ha^{-1} of soil) from the next depth increment is needed from the CT treatment to attain an ESM as that contained in the top 30 cm in the NT treatment. If a C concentration equal to the average between the 30 and 40 cm depths is used (5.9 g kg^{-1}), the C in this additional mass of soil is 2 Mg ha^{-1}, reducing the difference between the two treatments from 4 to 2 Mg. Another example, using a 7 year wheat-corn rotation in China (Table 1b; Du et al., 2010), showed that CT had 0.7 Mg C ha^{-1} less than NT by the fixed depth method but CT had 0.6 Mg C more than NT by the ESM method (Table 1b).

A number of ESM methods are available including the original method of Ellert and Bettany (1995), maximum and minimum ESM (Lee et al., 2009), cumulative mass coordinate (Gifford and Roderick, 2003), material coordinate system (McBratney and Minasny, 2010), and the most recent cubic spline method (Wendt and Hauser, 2013). Lee et al. (2009) compared the original ESM, maximum, and minimum ESM against the fixed depth approach and concluded that fixed depth approach is not appropriate and can be less accurate than simply reporting soil C concentration. They also showed that not all ESM methods yielded the same results. Wendt and Hauser (2013) compared the cumulative mass coordinates and cubic spline function against the original ESM method (Ellert and Bettany, 1995) and found that these three gave the same soil C results. While any ESM method is better than the fixed depth method, there are still some advantages and disadvantages among all ESM methods. To date, most researchers, if not all, have used the original ESM approach (Ellert and Bettany, 1995) but the cumulative mass coordinates and cubic spline function appear to have the best potential for more widespread use as these methods incorporate the bulk density measurement with the soil sampling and thus do not require a separate, tedious measurement of bulk density.

Sampling depth is also critical for comparing CA with conventional practices. The IPCC reference depth is 30 cm (IPCC, 2006) but many advocate sampling deeper than 30 cm, even up to 100 cm (Baker et al., 2007; Blanco-Canqui and Lal, 2008; Boddey et al., 2010). Referring to the studies in Tables 1a and 1b, the soil C concentration and bulk densities among treatments do not differ after 30 cm layer in the study by Du et al. (2010), whereas the differences are still evident as deep as 40 cm in the study by (Plaza-Bonilla et al., 2010). Boddey et al. (2010) suggested that increasing sampling depth to 100 cm may in fact lead to reduced estimates of C sequestration in NT in temperate systems but may increase estimates on NT in the well-structured Oxisols of the tropics and subtropics.

In summary, for the purposes of comparing soil C stocks of different soil management and tillage systems and the prominence given to soil C sequestration as a climate mitigation strategy, we recommend:

Sampling and reporting soil C on an ESM basis either with the original ESM or cumulative mass coordinate/cubic spline method and sampling to a depth of at least 50 cm plus 10 cm to adjust for ESM if needed.

Revising the IPCC protocol to compare C stocks on an ESM basis to a depth of 50 cm. The IPCC protocol currently used the fixed depth method and has a reference depth of 30 cm (IPCC, 2006) and may not capture the C changes resulting from management practices.

2.1.4. Summary, information gaps and research recommendations

1. Earlier reviews indicated that CA had considerable potential for storing soil C (West and Post, 2002; Lal, 2004). This optimistic view has been scaled back and it is now recognized that soil C storage with CA practices compared to conventional shows considerable variation, including some studies showing a decrease in soil C with CA. It is not clear for those studies that showed increased soil C with NT what factors differentiate them from the studies that do not show increases. As mentioned earlier, those determining factors can be climate, soil type, amount of residues, type of crops included in rotations, duration of the study or other factors.

Achieving a predictive understanding of the impacts of CA practices on soil C requires an integrated approach that links crop production to generation of inputs of crop residues and roots, and finally to soil C formation and decomposition. Unfortunately there is a lack of information provided in most CA studies or studies comparing different CA practices such as detailed soils information, the amount of residues returned or cover crop biomass, root biomass and rooting patterns, all of which are necessary to understand the factors and processes resulting in the observed soil C storage differences with CA. This lack of supporting data hinders a predictive understanding of where and under what management practices CA results in increased soil C storage, though some general insights are emerging. Future studies should follow standard data collection in CA experiments (Brouder and Gomez-Macpherson, 2013).

2. The amount of residues retained in the system is key component to the amount of C stored in the soil but there is little indication of the amount of residues needed to maintain or increase soil C. Data on the amount of residue produced and how it is managed should be linked to crop productivity levels to allow for predictive capabilities through simple relationships or for use in detailed process models. The amount of residues required to increase soil C and benefits derived from it depends on the crop types, yields obtained, and the balance between C inputs and decomposition which vary with soils and climate. Soil C models should be used more to understand these complex interactions and the relative importance of the different factors.

3. There are relatively few studies on C sequestration from low input, smallholder farming systems in tropical regions, limiting the ability to assess the effectiveness and feasibility of CA under these circumstances. We compiled ten studies from Sub Saharan Africa, only four met the criteria of sampling to at least 30 cm and a duration of 5 years or more but they only reported %C and not bulk density. A review of soil carbon sequestration in Africa by Vagen et al. (2005) was only able to report results to a depth of 10 cm, the most common sampling depth. The lack of longevity (> 5 years) and sampling problems does not allow valid comparisons of soil C sequestration of CA and conventional practices. On-going experiments should be maintained and resampled using the methods recommended in this paper. New experiments should be commenced replicating smallholder management in strategic agro-ecological zones. These new experiments should also reflect different levels of residue inputs and N fertilization rates to reflect current practices and increased rates that are required increasing yields in the region.

4. Using ESM soil sampling methods is essential for measuring and comparing soil C stocks between CA and conventional practices, especially when comparing different tillage practices. Comparing different ESM methods is needed to develop a simple, standard, and unbiased recommendation. We also recommend recalculating soil C stocks according to ESM methods as was shown in Table 1, as existing data permits. The current summary is likely biased to include more studies with significant C storage due to the fixed depth method.

2.2. Climate regulation – emissions of greenhouse gases

In this section we deal with the net emissions of N_2O and CH_4 from soils as a result of CA practices. It is also important to note that there can be considerable impacts of CA compared to conventional agriculture with changes in the intensity of mechanical tillage, less irrigation, and possibly less N fertilization and the associated reduced use of fossil fuels with CA (Pathak, 2009; West and Marland, 2002). These effects are not considered in this paper.

2.2.1. Nitrous oxide

N_2O is a potent and long-lived GHG, having a global warming potential 298 times that of carbon dioxide (CO_2) and remaining in the atmosphere for up to 114 years. N_2O is produced in soils in the microbiological processes of nitrification and denitrification. Nitrification - the oxidation of ammonium to nitrate - occurs in aerobic conditions while denitrification - the reduction of nitrate (NO_3^-) to N_2O and N_2 - takes place in anaerobic conditions. The relative contribution of these two N pathways to N_2O formation depends on episodic changes in soil aeration and water filled pore space (WFPS).

The frequency and magnitude of N_2O emissions is linked to soil structure which is a function of bulk density, soil C and aggregation, all influenced by tillage practices and residue inputs. Nitrification is the main source of N_2O at low WFPS below 40% (Dalal et al., 2003; Kiese et al., 2002; Werner et al., 2006) while the contribution from denitrification increases above 65-75% WFPS. The N_2/N_2O ratio increases with little N_2O produced at WFPS above 80-90% (Weier et al., 1993; Dalal et al., 2003). Soil bulk density is generally higher with NT compared to conventional practices; therefore, WFPS is higher so anaerobic conditions and denitrification are potentially induced sooner at the same water content with NT.

Residues management and crop rotations can affect N_2O emissions by altering the availability of NO_3^- in the soil, the decomposability of C substrates (Firestone and Davidson, 1989). The reduction of N_2O to N_2 is inhibited when NO_3^- and labile C concentrations are high (Hutchinson and Davidson, 1993; Weier et al., 1993; Senbayram et al., 2012). The retention of crop residues and higher soil C in surface soils with CA play major roles in these processes. Under anaerobic conditions associated with soil water saturation, high contents of soluble carbon or readily decomposable organic matter can significantly boost denitrification (Dalal et al., 2003) with the production of N_2O favored with high quality C inputs (Bremner, 1997).

Emissions of N_2O increase with applications of N fertilizers by increasing N availability in the soil (Davidson, 2009). The quantity and quality of residues or cover crops of CA systems can also affect N_2O emissions. Legume residues can result in higher N_2O–N losses (Baggs et al., 2000; Huang et al., 2004; Millar et al., 2004) than those from non-legume, low N residues (Aulakh et al., 2001; Millar et al., 2004; Yao et al., 2009). The N_2O emissions with legume N-rich residues compared to N mineral fertilizers, however, is lower per unit N added compared to the inorganic source (Baggs et al., 2000). One the other hand, low quality cereal crop residues (C:N ratio generally greater than 25) combined with surface application of residues in CA systems could result in immobilization of N and ultimately decreased N_2O production compared to conventional systems. Though legume residues may lead to higher N_2O emissions than cereal residues the quantity of legume residues returned to soil is substantially less (Peoples et al., 2009). The net result of CA on N_2O emissions will depend on the crop rotation practices and the types and amounts of crop residue in CA systems compared to conventional.

There is no clear response on the effects of NT or RT compared to CT on N_2O emissions (Snyder et al., 2009). With NT, residues are returned to the soil resulting in surface mulches which may lower evaporation rates and hence increase soil moisture and increase labile organic carbon C (Galbally et al., 2005) and consequently increase N_2O emissions compared to CT. Increased bulk density with CA compared to CT may also increase emissions. On the other hand, lower soil temperatures and better soil structure under NT may reduce the incidence of soil saturation and reduce emissions of N_2O.

Evidence from the field shows wetter soil conditions combined with higher available C under NT increase emissions of N_2O (Liu et al., 2006; Regina and Alakukku, 2010; Venterea et al., 2005; Yao et al., 2009). Studies in Australia show large effects of tillage with 0.13% and 15.4% of applied NO_3^- lost as N_2O from CT and NT, respectively (Dalal et al., 2003). Other studies have reported lower N_2O emission under NT or RT (Almaraz et al., 2009; Mutegi et al., 2010; Pandey et al., 2012; Smith et al., 2012; Ussiri et al., 2009; Wang et al., 2011) or no difference in emissions (Bavin et al., 2009; Fuss et al., 2011; Garland et al., 2011; Lee et al., 2009; Oorts et al., 2007; Pelster et al., 2011). Rochette's (2008) extensive summary concluded that NT only increased N_2O emissions in poorly aerated soils. Interestingly, many of the studies showing no difference include a high proportion of longer term trials where CA practices have been imposed for considerable periods of time. This observation is consistent with Six et al. (2004) who found N_2O emissions from NT declined with time.

The inconsistent results of N_2O emissions with CA practices are potentially due to the lack of comparability of studies and methodological issues on the measurement of N_2O in the field. These issues include 1. a lack of long-term observations at any site, most studies are single season or from one year of measurements, 2. the high temporal and spatial variability in N_2O, and to a lesser extent CH_4, emissions, and, 3. problems associated with chamber based field methodologies. For example, sampling frequency varies from several days to one month with interpolation to develop seasonal N_2O emissions estimates. Annual N_2O emission estimates can be overestimated by nearly 200% if measured only every 30 days (Rowlings et al., 2013) as highly significant episodic events are missed. Fuss et al. (2011) observed consistently lower background emissions in NT to CT but consistently higher emissions in NT till during the high magnitude episodic events. The diurnal patterns of emissions are also not captured in most chamber based studies.

2.2.2. *Methane*

Methane has a lifetime of 12 years and a global warming potential 25 times that of CO_2 over a 100 year time horizon. Agricultural soils contribute to CH_4 emissions as a result of methanogenic processes in waterlogged conditions that are usually associated with rice production. Flooded rice production contributes 15% of total global CH_4 emissions (IPCC, 2001). The magnitude of CH_4 emissions is primarily a function of water management with the addition of both mineral and organic fertilizers having a significant influence. The addition of organic fertilizers has the potential to increase emissions by over 50% relative to non-organic fertilizers (Denier van der Gon and Neue, 1995; Yagi et al., 1997; Yao et al., 2009).

In contrast to N_2O (Chapuis-Lardy et al., 2007), CH_4 can be consumed (oxidized) by soil microorganisms and resulting in a CH_4 sink which is sensitive to both temperature and soil water content (Dalal et al., 2008; King, 1997). The total CH_4 flux from soils is therefore the difference between the production of CH4 under anaerobic conditions and CH_4 consumption. Agricultural soils, particularly those that have been fertilized, have a significantly lower CH_4 oxidation rate compared to natural soils (Bronson and Mosier, 1993; Jacinthe and Lal, 2005; Smith et al., 2000) and higher oxidation rates are observed in temperate compared to tropical soils (Dalal et al., 2008). The effect of tillage practices on the rate of CH_4 consumption, in general, depends on the changes in gas diffusion characteristics in soil (Gregorich et al., 2006; Hutsch, 1998). A decrease in CH_4 consumption and a potential net emission of CH_4 could be expected with RT or NT due to increased bulk density and WFPS. Yet no significant tillage effect on CH_4 oxidation rates have been detected (Bayer et al., 2012; Jacinthe and Lal, 2005; Smith et al., 2012).

Evidence supporting a decrease in CH_4 oxidation or an increase in CH_4 emissions with crop residue retention under CA is more conclusive than for N_2O. Residue retention provides a source of readily available C, which enhances CH_4 emissions from rice paddies which are generally under anaerobic conditions (Cai et al., 1997; Watanabe et al., 1995; Zou et al., 2005). Crop residues may affect CH_4 oxidation in upland soils and emission patterns in flooded soils differently depending on their C/N ratio; residues with a high C/N ratio have little effect on oxidation while residues with a narrow C/N ratio seem to inhibit oxidation (Hiitsch, 2011).

Flooded rice (with the practice of puddling the soil) is a large contributor of CH_4 emissions from agriculture. Reduced or NT is currently being promoted in the Indo-Gangetic Plains (IGP) in rice-wheat systems (Gathala et al., 2013) With this system, direct-drill seeded rice does not require continuous soil submergence, thereby could either reduce or eliminate CH_4 emissions for lowland rice when it is grown as an aerobic crop (Pathak, 2009). The overall impact of RT in this environment, however, appears to be relatively minor. Grace et al. (2012) estimated an average of 29.3 Mg ha^{-1} of GHGs emitted over 20 years in conventional rice-wheat systems across the IGP; this decreased by only 3% with the widespread implementation of CA.

2.2.3. *Summary, information gaps and research recommendations*

1. The lack of definitive conclusions and contradictory findings on N_2O emissions from CA compared to conventional practices highlights the multitude of factors that effect N_2O emissions. Some of the factors that increase N_2O emissions also lead to increased CH_4 emissions or decreased CH_4 oxidation yet the thresholds and management practices to mitigate these different gas emission pathways are not necessarily the same. Studies examining the impact of different CA practices on all relevant GHGs, including soil C sequestration, and the resulting net global warming potential are rare, yet such studies are crucial for developing comprehensive management options for climate change mitigation in different environments. One of the few comprehensive studies over multiple years (Dendooven et al., 2012a, 2012b) found no differences in either N_2O or CH_4 emissions between CA and CT in a long term

dryland cropping trial in central Mexico. CA was found to have a significantly lower global warming potential in comparison to CT due to the changes in soil C alone. Datasets from such studies are needed to investigate the relative roles, interactions and impacts of residue management, tillage, cropping systems, and nutrient management on soil physical and chemical properties and the resulting GHG emissions and crop yields for different climate and soil types. The current information is fragmented and poorly documented and its interpretation is potentially confounded due to the lack of information on the major controlling variables. These datasets should be coordinated with on-going CA trials and other crop-soil simulation initiatives to ensure maximum utility and cost-effectiveness.

An more mechanistic understanding of soil N dynamics with CA could lead to improved management strategies which increase N use efficiency and reduce N_2O emissions (and N losses generally). In particular, the net emissions related to the types (quality) and amounts of inputs from crop residues or different rotations with cereals and legumes and cover crops as they affect N and C availability and N_2O and CH_4 emissions needs to be elucidated for selection of the rotations and residues types that minimize net emissions while not compromising yields. Improved understanding of management strategies that alter the N_2O/N_2 ratio could also prove effective in mitigation combined with improved N use efficiency.

Management strategies that can be aligned with NT to keep soil in the oxidative state and promote aerobic organic matter decomposition are potential mitigation strategies for reducing CH_4 emissions (Ortiz-Monasterio et al., 2010). Reducing the duration of flooding is also being promoted as a practical solution to reduce CH_4 emissions in CA rice production systems generally, but these may be offset partially by an increase in N_2O emissions (Ortiz-Monasterio et al., 2010).

2. Periodic sampling methods commonly used for measuring greenhouse gas emissions can lead to incorrect estimates and increase the uncertainty surrounding the impact of CA practices. Advances in the use of low cost portable, automated chamber and analysis systems in recent years is tackling many of these sampling related problems (Rosenstock et al., 2013; Rowlings et al., 2012; Scheer et al., 2012a,b; Werner et al., 2006; Butterbach-Bahl et al., 2002). Such systems should be included in future CA gas emission studies.

3. Soil quality, biodiversity and the regulation and provision of water and nutrients

Many ecosystem processes and ES are provided by soils and the biodiversity in them (Palm et al., 2007; Wall et al., 2004; Daily et al., 1997). Soil quality refers to a range of soil properties and functions that support plant productivity and ES (Oberholzer and Hoper, 2007; Karlen et al., 1997) and is assessed by soil biological, physical, and chemical means. Many soil quality properties are determined, in part, by soil texture and mineralogy but can be modified by soil organic matter (SOM) content and composition and the activities of soil biota (Palm et al., 2007) both of which are affected by management practices (Oberholzer and Hoper, 2007).

A review by Verhulst et al. (2010) provides a detailed assessment the effects of CA practices on soil quality compared with conventional practices. The reader is referred to this comprehensive review; a brief summary of the general trends is presented below and in Table 2. Verhulst et al. (2010) has been augmented by more recent research on CA and soil quality. The summary below follows the effects of CA on water and nutrient cycling and retention through changes in the biological, physical, and chemical aspects of soil quality.

3.1. Soil biological properties and ecosystem services

Soil organic matter is an integrator of several soil functions and as such is a key component of soil quality and the delivery of many ecosystem services (Palm et al., 2007). The CA practices of NT and residue retention are key to maintaining or increasing SOM in the topsoil which in turn provides energy and substrate for soil biota activities and their contributions to soil structure and nutrient cycling, as well as many other soil processes and ES (Brussaard, 2012). In general, CA practices increase SOM and other soil biological properties (Table 2a). These effects are, however, generally confined to the topmost soil layer (0-5 cm or 0-10 m) but are often not evident over 0-15 cm (Bissett et al., 2013; Verhulst et al., 2010).

These differences in SOM concentrations and distribution combined with lack of soil disturbance and crop rotations affect the abundance, diversity, community composition, vertical distribution within the soil profile, and activities of soil biota. These effects have concomitant changes in decomposition, nutrient cycling, bioturbation, soil aggregate stability, and other soil ecosystem services (Bignell et al., 2005). Biodiversity is often considered fundamental to the delivery of ES and especially the stability of delivery of these ES (Naeem et al., 2012). These relationships between biodiversity and ecosystem functions and services are complex; providing evidence and predictive understanding has been difficult (Naeem et al., 2009). CA alters below and above ground species differentially than conventional agricultural practices (McLaughlin and Mineau, 1995). This alteration in species drives a range of responses among different groups of organisms but most have greater abundance or biomass and diversity in NT than in conventional tillage (Table 2a; Gonzalez-Chavez et al., 2010; Rodriguez et al., 2006). These changes likewise have important effect on components of soil quality that are biologically mediated. In order to elucidate the contribution of biodiversity to service provision it is often grouped into pseudo functional groups based on body size and gross function (Kibblewhite et al., 2008; Bignell et al., 2005). Although these classifications mask important distinctions, they are useful to categorize information on soil biota especially when the taxonomic status is unclear and difficult to classify. More importantly it is the function of the biota that is important for ecosystem services rather than the taxonomic status.

Soil microbial biomass, composed primarily of bacteria and fungi, is an indicator of soil quality due to its role in decomposition, nutrient cycling rates and patterns, formation of SOM, and soil aggregation. Microbial biomass is generally higher with residue retention. Reduced tillage is a secondary factor. Some authors have stated that fungal communities tend to dominate the soil surface of NT, whereas bacterial communities dominate in conventional tillage systems (Verhulst et al., 2010). This difference results in slower rates of nutrient mineralization and higher nutrient use efficiency with surface residue retention compared to conventional systems. Other long term studies however were not able to identify this shift between fungi and bacteria (Helgason et al., 2009) with minor overall impacts on decomposition and nutrient availability more likely (Bissett et al., 2013). The impacts of a shift in microbial composition may become more important on degraded soils (Verhulst et al., 2010). Fungi, particularly arbuscular mycorrhizal fungi, are also important for nutrient acquisition and drought resistance, particularly for low nutrient input systems. They also play a key role in forming stable soil aggregates. Hyphal length is shortened with tillage so the effects on aggregation and nutrient and water acquisition would be higher in CA compared to conventional (Oehl et al., 2005).

Earthworms play a significant role in maintaining soil structure and nutrient cycling by their movement through the soil, by breaking down litter, and by binding soil particles with their excrement. They create stable soil aggregates as well as macropores,

Table 2
Soil properties and processes as related to a) physical properties and processes and related water provision and regulating services, b) soil chemical processes related to nutrient cycling and retention, and c. soil biological properties as related to nutrient cycling, water infiltration, and pest control. The information is summarized from Verhulst et al. (2010); columns compare the properties, processes and ES between no-till (NT) and conventional tillage (CT) and surface residue retention vs no surface residue placement.

a.

Soil biological properties and processes	NT compared to CT	Residue retention
Soil organic matter in topsoil	↑	↑
Particulate or labile organic matter fractions	↑	↑
Soil microbial biomass	↑	↑
Microbial functional diversity	↑	↑
Fungal populations	↑	↑
Enzymatic activity	↑	↑
Beneficial micro-organisms (fluorescent Pseudomomas; Actinomycetes, some Fusarium strains)	↑	↑
Pathogenic micro-faunal: Take-all Gaeumannomyces; Rhizoctonia, Pythium, and Fusarium root rots	↑	↑
Free-living (beneficial) nematodes	ns	↑
Plant-parasitic nematodes	↓	ns
Earthworms	↑	↑
Arthropod diversity	↑ more so for predators then phytophagous arthropods	↑

b.

Soil physical properties, processes and ecosystem services	NT compared to CT	Residue retention
Aggregate stability	↑	↑
Bulk density	↑ but small number of studies showing opposite	↓
Total porosity	↓	↑
Macropores	↓↑ avg size larger	↑
Mesopores	↑	
Micropores	↑	
Hydraulic conductivity	↓ mixed results	↑
Infiltration	↑	↑
Runoff	↓	↓
Evaporation	↓	↓
Plant available water	↑	↑
Erosion	↓	↓

c.

Soil chemical properties, processes and ecosystem services	NT compared to CT	Residue retention
Total nitrogen	↑ follows pattern of soil organic matter	↑
Nitrogen availability (N mineralization)	generally ↓ at least in the short term and often long term	↑↓ depends on quality of residues
P, K, Ca, Mg	P ↑ in top soil layer. K ↑ in surface layers, in general. Ca, Mg few differences	K depends on type of crop residue
Cation exchange capacity	no effect	↑ but only in very top layer
pH	more often ↓	↓
Nutrient leaching	??	??

both critical for soil and air movement, and they decompose and ingest organic materials increasing nutrient availability in soils. Earthworms are divided into three broad functional groups and size classes, the presence of all three appear necessary for maintaining soil structure (Verhulst et al., 2010). Reduced tillage and residue retention are both important for maintaining a stable environment (less physical disruption and higher soil moisture content, respectively) that favors earthworms, which are found to have higher abundance and diversity with CA compared to conventional systems (Table 2a; Nieminen et al., 2011). Differences in the composition of the earthworm community likely result in larger and more connected soil macropores in the CA system compared to conventional, with concomitant impacts on water infiltration and water regulation. A predominance of the large size class of earthworms can result in surface sealing and decreased infiltration (Verhulst et al., 2010).

3.2. Soil physical properties and ecosystem services: water infiltration, runoff-erosion, water quality and available water

Erosion control is a main objective of reduced tillage and residue retention, contributing to both on-, and off-site ecosystem services. Reduced or NT and surface applied residues directly reduce erosion by minimizing the time that the soil is bare and exposed to wind, rainfall and runoff. CA and NT can reduce wind erosion due to the larger proportion of dry aggregates, less wind erodible fraction and greater crop residue cover of the soil surface (Singh et al., 2012; Verhulst et al., 2010). CA can also indirectly reduce erosion by water through the effects on soil properties and processes that increase water infiltration and reduce runoff. A summary of these effects show which soil physical properties are responsive to tillage and residue management (Table 2b). No-till management generally increases bulk density of the topsoil, reduces total soil porosity, and even hydraulic conductivity compared to CT systems. These changes would be expected to lower water infiltration rates in NT compared to CT; this however has not been shown–instead an increase in infiltration has been reported with NT. When residues are removed the reverse trend is observed (Kahlon et al., 2013; Verhulst et al., 2010). These somewhat contradictory effects of increased bulk density and reduced porosity but increased infiltration are likely due to the increased organic matter and biotic activity in the surface soil with surface residues and NT which lead to increased stability of soil aggregates and greater macropore connectivity from macrofaunal activity. Increased water infiltration translates into reduced water runoff and erosion with CA. There are fewer studies assessing crop rotation impacts on soil physical properties but thus far have shown few significant effects (Thierfelder et al., 2013b; Verhulst et al., 2010).

Although the rates of erosion depend on soil type, topography, climate, and rainfall duration and intensity, repeated studies have shown signification reductions with CA practices compared to conventional practices in a range of conditions at field scale (Meijer et al., 2013; Montgomery, 2007; Zhang et al., 2007), at watershed/catchment scales (Prasuhn, 2012) and with climate change simulations (Zhang, 2012). Runoff and erosion are typically reduced by an order of magnitude with NT compared to conventional (Kay et al., 2009; Prasuhn, 2012).

Reducing runoff and water erosion with CA should result in lower transport of sediments, nutrients and pesticides/herbicides and higher water quality. With NT or conservation tillage, N in sediments and runoff water have been reduced by as much as 60% (Kay et al., 2009) though there is a wide range with only a 9% reduction of N in runoff recently modeled by Liu et al. (2013a). Nitrogen losses in sediments were consistently lower with NT in a study by Richardson and King (1995) but losses of soluble N differ with the type of crop, with less soluble N lost with wheat compared to maize or sorghum. There are consistent reductions in P losses to surface waters with NT and herbicides in runoff have been reduced by 40 to 70% with NT (Richardson and King, 1995). The situation with pesticides is less straightforward. Though pesticides in runoff have been reduced by 40 to 70% with NT, the concentration of pesticides in runoff water can be higher than with CT, the overall impact is less clear (Kay et al., 2009). Some recommend incorporation of pesticides to increase absorption by soils, thus reducing losses by runoff or leaching (Kay et al., 2009; Reichenberger et al., 2007). In effect there are somewhat contradictory recommendations for reducing pesticide losses, NT to reduce losses by runoff and erosion but tillage to reduce losses by leaching. Similar types of factors need to be considered in determining the extent of nitrate leaching into groundwater (Verhulst et al., 2010). In general more research on the impacts of CA practices on water quality are needed.

Conservation agriculture practices result in more plant available water than conventional practices. This is a result of increased water infiltration and lower evaporation with reduced mixing of the surface soil, more residue cover and less exposure to drying compared to conventional tillage. Water holding capacity of the topsoil is also generally higher due to increased SOM contents. Liu et al. (2013b) found soil moisture content was most affected by residues compared to tillage practice; soil moisture remained highest throughout the growing season with NT plus residue, intermediate levels of soil moisture with tillage plus residues, and lowest levels with NT without residues. Likewise Thierfelder et al. (2012, 2013b) found higher soil moisture contents in Zambia for each of five years with NT and surface residue compared to CT with residues removed. These difference extended beyond 30 cm in some years. This increased water content in the topsoil CA would be especially important for crop growth during prolonged dry periods with less variable yields than conventional practices. This effect of increased soil moisture with NT and residue retention compared to CT without residues resulted in 1.5 Mg ha^{-1} higher maize yields annually over a 12 year period, with large differences (4.7 Mg) in years with long dry spells (Verhulst et al., 2011). Thierfelder et al. (2013a) found higher infiltration rates with CA practices of RT and residues compared to conventional at several sites in Malawi; these difference were also reflected in higher yields though the effect differed by site and duration of practices.

The impact of higher soil moisture with NT on yields or water use efficiency is also shown with irrigation. Studies have shown a 20-50% reduction in irrigation water with NT and residue retention with similar or higher crop yields (Grassini et al., 2011; Gathala et al., 2013). Verhulst et al. (2011) found higher yields with CT compared to NT with full irrigation in Mexico but no difference or higher yields under NT under reduced irrigation levels due to higher soil aggregation and increased infiltration rates.

3.3. Soil chemical properties and ecosystem services: nutrient cycling and retention

The distribution of organic soil N in the soil profile under CA is similar to that of soil C (Table 2c), though N availability, as measured by extractable mineral N, differs by studies and is confounded by rates of fertilizer N applications and the quality of crop residues or cover crops (Bissett et al., 2013; Powlson et al., 2011b; Bhardwaj et al., 2011). Nitrogen availability is often lower in CA systems due to slower decomposition and higher N immobilization with surface application of residues than in conventional practices (Boddey et al., 2010; Verhulst et al., 2010). The low quality surface residues may result in temporary N immobilization of fertilizer N, with higher N use efficiency and reductions of fertilizer N applications for similar crop yields (Bhardwaj et al., 2011). With low N input systems, though, this slower release of N may further reduce crop yields (Nyamangara et al., 2013). Higher N use efficiency and lower levels of soil inorganic N with CA may also result reduced N leaching. There is also a contradictory hypothesis that nitrate leaching is greater in CA due to higher mass water flow through more connected macropores compared with conventional practices (Kay et al., 2009).

Soil nutrient differences as a result of CA practices are often confounded because mineral fertilizers are also applied. Potassium and phosphorus are concentrated and more available in the surface soils (0-5 or 0-10 cm) with NT and residue retention and exhibit a greater decrease with depth than conventional practices (Table 2c). Increases in potassium are usually attributed to the high concentrations in cereal crop residues, while phosphorus availability due to a a decrease in P-sorption with higher SOM content in CA topsoil. These differences in nutrient concentrations and distribution were not reflected by difference in plant nutrient concentrations but were reflected in higher yields with reduced tillage (Hulugalle and Entwistle (1997). Concentration of nutrients in the superficial soil layers with CA practices could present problems in years with prolonged drought periods because the roots could be distributed more superficially where nutrients are concentrated (Paul et al., 2003) but this may be offset by higher soil moisture in CA.

3.4. Relationship of soil quality to soil processes and ecosystem services

Soil quality is key to crop production and several ES. Some soil quality indicators relate fairly directly to an ES, such as soil aggregation and macroporosity to soil water movement. Sometimes, however, several soil quality indicators may be correlated to ES delivery, but often it is not clear which of the numerous soil quality parameters are essential for the maintenance of that ES. Contradictory results from studies comparing soil quality parameters from CA or conventional practices (Bissett et al., 2013; Verhulst et al., 2010) also make it difficult to distinguish the key components of soil quality related to ES delivery. Similarly there is scant information on threshold levels of soil quality indicators required to deliver these ES.

A study by Bhardwaj et al. (2011) approached this issue by looking at the relationship of 19 soil quality variables with crop production in several cropping systems including no till. They found that nine of the 19 variables did not show significant differences among treatments. Through principal component analysis they narrowed the variables to six including pH, NO_3^--N, NH_4^+-N, bulk density, soil aggregate stability, and N nitrification. They assessed these six variables and computed an integrated soil quality indicator (SQI) for the different treatments and related it to crop production. Several treatments had similar yields (conventional, no-till and reduced input) but with different impacts on soil quality components and SQI. Reduced till exhibited the highest SQI while conventional was fourth out of five treatments. A message from this study is that one of the CA practices, NT, can maintain yields and soil quality parameters related to other regulating ES. A similar analysis was used by Thierfelder et al. (2013b) to determine the relative effects SOM, aggregate size and stability, and infiltration on crop yields in Malawi. Though the influence of CA on soil properties differed by site there was an overall greater contribution of SOC and infiltration to maize yields. Kirkegaard (1995), on the other hand, found that while NT may have positive effects on reducing erosion it may not be accompanied by increases in yields; likewise Richardson and King (1995) found a reduction in erosion and runoff but a reduction in yields on a clayey soil, especially during wet years.

Integrated studies and assessments such as these are needed in CA to identify the key soil properties (and related processes) that contribute to crop production as well as to the regulating ES that are related to resource use efficiency and reduced losses to the environment. The key soil variables and components will likely change with soil type, climate, and time under CA but patterns could emerge with a network of trials.

3.5. Summary, information gaps and research recommendations

1. The CA practices of residue retention, NT, and certain crop rotations increase SOM in the topsoil that, in turn, impact soil physical properties and process that reduce erosion and runoff and biological and chemical properties that could lead to improved N use efficiencies and fewer N losses to the environment. The amount of SOM that is needed to drive these changes in soil properties and processes and related ES is not well known. Few studies have quantified the linkages among these different soil properties and processes and their relationships with the provision and regulation of nutrients and water and with crop productivity as the measurements are often taken by different groups of investigators.

Existing CA experiments or strategically placed and newly designed experiments should be used for a comprehensive comparison of CA with conventional practices in a range of soils and climates. These experiments should include integrated assessments of the linkages of SOM with other soil quality parameters in relation to the actual delivery of ES. Threshold levels of SOM and the management practices needed to attain and maintain those levels could be investigated, including the time needed to achieve those levels of SOM. These studies could be the same experiments as discussed under soil C sequestration and greenhouse gases.

2. Soil physical properties such as aggregation and macroporosity are important for determining rates of water infiltration, runoff, plant available soil water, erosion, and others. These factors are usually greater with CA and are related to reduced erosion and runoff. Though there are fewer studies on water quality, in general, less sediment load and reduced N are observed with CA. There are some key questions that if addressed could identify the key CA practices that are required for maintaining or improving soil physical properties related to the ES of water regulation and provision on different soil types. Currently there is insufficient information to synthesize results according to soil type.

- What is the amount of crop residue needed to improve and maintain soil properties and processes that result in reduced water runoff and soil erosion, or increased soil moisture levels? Govaerts et al. (2007a) suggest that it is possible to remove 50–70% of the crop residue while keeping adequate benefits to the soil but residue removal in excess of 50% have adversely affected soil quality as well as crop yields in the US (Blanco-Canqui, 2010). Recommendations for the amount of residue removal will depend on climate, soil type and topography. Whilst Blanco-Canqui and Lal (2008) stress those similar recommendations may hold for cropping systems on heavy textured, flat soils in temperate regions, no residue should be removed from sloping and erosion-prone soils under NT conditions. Advice to remove half the residue would not hold for systems with low crop and residue production. In smallholder farming systems in Sub Saharan Africa and South Asia, there may be insufficient residue produced or retained due to other competing uses to provide these ES. Relating the amounts and types of C inputs required for delivering ES would be useful for assessing the feasibility of CA and better adapting CA management practices as needed (Baudron et al., 2013) for different climates and soils.
- What levels of increased soil moisture content with CA result in higher crop productivity and/or less variable production with climatic variability? Studies along these lines are emerging but more studies are needed on a range of soils and CA practices. Such information will be especially important for drought prone areas and sandier soils.

3. A combination of soil biological and chemical properties and process determine N availability patterns. Differences in N availability between CA and conventional practices are sometimes implied as increased retention and nutrient use efficiency in CA systems compared to conventional. Few studies have documented these aspects, particularly with crop residues and crop rotations with different proportions of cereal crops and legume crops or cover crops. Further research should address the differences in N availability patterns and distributions, N use efficiencies and N losses under different CA crop rotations.

- How do crop rotations with legumes (and which legumes) affect N availability and use efficiency differently in CA compared to conventional systems?
- Does increased N use efficiency translate into reductions in the amount of fertilizer N needed to attain the same yields as with conventional agriculture?
- Do the different patterns of N availability (increased immobilization and slower release) with CA result in decreased N leaching? Currently there are opposing processes that have been proposed, one that less available N results in less leaching and another that increased macropore continuity with CA will lead to increased losses of N through leaching. Answering this question requires combined information on infiltration, N concentrations and leaching–currently data that are often collected by groups with different interests so are not collected in the same experiments.

4. Few linkages have been made between soil biodiversity and ES though they are often implied by the occurrence of different soil functional groups between CA and conventional practices. Different studies report quite varied effects of CA practices on soil biological properties and soil biota. These differences are often related to different soils and climates, crop types and rotations, intensity of tillage, timing of operations, time of sampling, the suite of management practices, and the depth of the soil studied (Kladivko, 2001). It would be of value to determine if broad patterns exist between soil biotic abundance and functional diversity as modified by CA and the soil properties and processes and ES service provision in different environments. Such research would require using standard methods and comparisons among similar treatments across different environmental situations but would be useful to build a database on the value of biodiversity and ES under CA.

4. Other ecosystem services and biodiversity

Although not a focus of this paper, it is important to point out a few other ESs and the underlying biodversity that are relevant to CA compared to conventional agriculture. CA management practices can affect habitat suitability for soil pathogens or alter community composition of the predators or parasites of major disease organisms compared to conventional practices. More diverse soil communities suppress the impacts of the pathogens (Verhulst et al., 2010). Higher SOM levels with CA produce cooler and moister conditions favorable to pests and diseases and many fungal pathogens reside in crop residues of the host crop and thus may increase incidence and disease retention time in the soil (Cook, 2006). Crop rotations can reduce population size of these pathogens and change soil community composition (Cook, 2006). Soil borne pests and diseases such as fungi and nematodes are affected by CA practices (Table 2a) though the effect on these populations is mixed (Schroeder and Paulitz, 2006). A review by Stinner and House (1990) indicates that although some soil borne pests increase with NT, more pathogens actually declined with NT. No-till, irrespective of plant residue retention, has generally decreased the impact of pest species while residue retention is thought to increase disease incidence, at least in the first years of transition to CA (Verhulst et al., 2010). Increasing tillage frequency disrupts community diversity and stability and has a greater negative impact on species with slower response rates to disturbances; this typically includes loss of species higher in trophic chains, such as predators and parasites of disease organisms. A transition to NT allows the recolonization of such species. Crop rotations have shown reductions in pathogen populations that are usually associated with yield reductions but direct linkages are less clear.

The combined effects of CA lead to a more diverse and stable soil community, including beneficial bacterial and fungal species that can suppress pathogens (Verhulst et al., 2010; Lupwayi et al., 1998). Increased abundances of meso-fauna such as arthropods (Dubie et al., 2011; Tabaglio et al., 2009; Brennan et al., 2006) and macro-fauna such as spiders and hymenopteran parasitoids have been found with NT (Rodriguez et al., 2006; Marasas et al., 2001; House and Stinner, 1983; Stinner and House, 1990). Abundance and diversity of populations of natural enemies of parasitic nematodes may be higher with NT (Verhulst et al., 2010). Studies have shown initial increases in pests and diseases with the implementation of NT and residue retention, followed by gradual decreases (Gerlagh, 1968; Shipton, 1972). It is assumed to be related to the re-establishment of more diverse communities with CA. While yield losses to disease are also reduced with time, pre-disease outbreak yields are not recovered. The balance of these pests and beneficial organisms determines the overall effect on crop production; however, there is little information of the functional relationships between beneficial and detrimental soil organisms and the ultimate outcome on productivity. These effects could be investigated in the set of field studies recommended for the other ES.

The effects of CA at the field scale can also be a mechanism though which biodiversity provides ES, particularly in heterogeneous landscapes (Fahrig et al., 2011). Two recent studies reported landscape scale effects of tillage on biodiversity and biological control. In the first study, the proportion of NT rape seed fields in a landscape was a predictor of parasitism rates by three univoltine parasitoid species (Rusch et al., 2011). In the second study, the proportion of RT fields at 1500-2000 m scales was positively correlated to parasitism rates on the pollen beetle in oilseed rape fields, showing an increase in biological control of this pest at the landscape scale related to RT (Rusch et al., 2012). The combined studies suggest that reducing field scale soil disturbance can have landscape scale impacts on ES, by providing more stable and diverse habitats that harbor parasitoids.

Studies of pollinators usually focus on the effects of herbicide applications. Several species of bees, however, use soil-based burrows and can be affected by soil disturbance. One study considered the impact of NT on pollinator diversity and found that pollinator abundance, particularly of the squash bee, was greater in NT than in CT (Shuler et al., 2005). In contrast, European honeybee abundance was not impacted by tillage. Most interventions to protect these key species have focused on conserving semi-natural vegetation in field margins or in push-pull systems. The combination of habitat provision and CA in providing ES of pest control and pollination similar to field margin conservation has not been sufficiently explored.

5. Conservation agriculture and ecosystem services in smallholder farming systems

Conservation agriculture is being promoted widely in many areas of Sub Saharan Africa and elsewhere in the tropics to recuperate degraded soils (Erenstein et al., 2008). Whilst CA has been successfully introduced in high input and high yielding smallholder systems in the rice-wheat region of South Asia, the low input, low productivity systems characteristic of much of Sub Saharan Africa requires attention. Although there are still insufficient long term CA experiments and on-farm studies in Sub Saharan Africa (Thierfelder et al., 2012) it is clear that the biggest obstacle to improving soils and other ES is the lack of residues produced due to low productivity (Paul et al., 2013; Thierfelder et al., 2013b, Dube et al., 2012; Lahmar et al., 2012; Ngwira et al., 2012; Giller et al., 2009; Hengsdijk et al., 2005). Increases in topsoil C, as observed for the majority of CA studies from temperate regions, are critical for recuperating soils and the numerous ES associated with it. Even in cases where increased topsoil C has been found in experimental fields in Sub Saharan Africa (Thierfelder et al., 2013b; Chivenge et al., 2007; among others) the studies may not reflect the amounts of residues found in farmers fields.

Insufficient levels of surface residue combined with NT does not result in increased SOM (Nyamangara et al., 2013), soil moisture (Liu et al., 2013b) or related ES and can even result in decreased yields (Blanco-Canqui, 2010; Giller et al., 2009). The amounts of residues required to deliver the different ES is not known. Several experiments in Sub Saharan Africa have shown increased and less variable crop yields due to increased soil moisture associated with surface residue retention and NT (Thierfelder et al., 2013a, 2013b; 2012; Verhulst et al., 2011). This benefit would be particularly important for many of the drier areas of Sub Saharan Africa, though the amount of residue required to retain soil moisture is not known.

Fertility management, particularly N, is required to increased production and residue inputs in these low productivity systems (Nyamangara et al., 2013; Dube et al., 2012; Giller et al., 2009). Nyamangara et al. (2013) even reported reduced yields with surface applications of mulch when no fertilizer N was added. Improved access to mineral fertilizers in Sub Saharan Africa will be essential to the feasibility of CA in the region. Legume cover crops or trees may also provide organic sources of N but probably not in sufficient quantities in early stages of soil (Lahmar et al., 2012).

The other constraint to sufficient levels of residue for CA in these smallholder systems is the multiple, economically important alternative uses of residues. Studies that investigate the amounts of residues required for providing ES are especially important such smallholder systems. Likewise, studies that investigate the costs or trade-offs incurred by farmers to retain crop residues relative to the gains in soil C (Giller et al., 2009), and other ES would be useful for developing incentives or payment for ES in order for farmers to be willing to retain residues. In mixed farming systems in Zimbabwe, increased use of small rates of fertilizer and manure resulted in an increase in biomass production, and partial retention of crop residues in the fields (Rufino et al., 2011).

All three CA practices are currently not part of the traditional practices in Sub Saharan Africa making their adoption challenging. While RT or NT may be accepted due to lower labor requirements, the frequent weeding required throughout the cropping season with NT may negate those effects (Mashingaidze et al., 2012). Residue retention will be difficult to achieve in areas with substantial livestock without increasing the amounts available and perhaps providing incentives. Acceptance of crop rotations may be limited in areas of chronic food insecurity and staple crop production until functioning markets are established (Thierfelder et al., 2012). All these limitations point to nuanced approach to CA or the promotion of the different CA practices in Sub Saharan Africa. A sequence of interventions, as suggested by Lahmar et al. (2012), may be more appropriate. The first step is to increase crop production through nutrient management, followed by soil and water management practices that improve soil quality and water retention, and then gradually the introduction of CA practices if and where appropriate to the soil, climate and socioeconomic conditions. These steps must be based on evidence that the practice or suite of practices result in increased ESs without compromising increased yields.

6. Conclusions

Conservation agriculture produces the soil conditions that result in reduced erosion and runoff and improved water quality compared to conventional practices. Likewise, water holding capacity and storage are enhanced with CA providing some buffer to crop production during drought conditions. SOM is almost invariably higher in the surface soil with CA practices compared to conventional practices and influences many other soil properties and processes involved in the delivery of ES. The deliveries of most other ES, including soil C sequestration, emission of GHGs, and pest control, are not so clear cut (as detailed in the section summaries). Some of the differences could be due to the duration of experiments or the experimental designs with some comparing NT, residue retention, or a combination of the two. The effects of crop rotation are less clear than for the other two practices.

There is currently insufficient information from CA studies to explain the inconsistent results. Many of these differences may be due to soil type, topographic position, parent material, climate and their combination, and interactions with management. Yet it is this type of information that is essential for determining where and why CA does work in delivering ES, while increasing crop production. The study of ESs in agriculture requires approaches and methods from both agronomy and ecology, a bridge that is all too often incomplete, yet is critical to understanding the underlying processes and controls that lead to changes in production and other ES. As examples, agronomists will often measure SOM levels in the topsoil because it relates to soil fertility but to determine the ES of soil C sequestration requires the measurement of the total stock of soil C deeper in the soil. This requires measuring %C in several layers of the soil profile as well as the bulk density of the soil. As a consequence, data gathered in agronomic trials of CA may not be sufficient to assess some ESs. Likewise, ecologists may measure soil biodiversity in different agricultural management practices but they may not connect them to measures of soil processes that are important for ES or measure the resulting crop production.

Unpacking the differential effects of CA management practices as well as their combination on soil process and ES and how these are modified by climate and soil type is necessary to develop a predictive understanding that can be used for improved, site specific CA management guidelines. In other words, to better assess, manage and target CA it is necessary to know the relative importance of tillage, residue management, crop rotations and their combination on the different ES and also how those ES relate to crop production. The types of experiments installed for testing CA and comparing with conventional practices (tillage, residue removal or incorporation and monocultures) do not necessarily have the design and controls that are required to separate the individual and combined effects of the different CA practices. Establishing a set of strategically located experimental sites that compare CA with conventional agriculture on a range of soil-climate types would facilitate establishing a predictive understanding of these relative controls of higher order factors (soil and climate) and management (tillage, residues, crop rotations) and ES outcomes, and ultimately in assessing the feasibility of CA or CA practices in different sites and socioeconomic situations.

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Appendix A. Studies comparing soil carbon, bulk density with depth in no-till (NT) and conventional tillage (CT). FD = fixed depth basis for assessing soil C stocks; ESM = equivalent soil mass basis.

Location, Reference, fixed depth or equiv mass	Rainfall (mm)	Soil Type	Years	Crop Rotation	Soil Depth (cm)	Bulk density CT (Mg/m^3)	Bulk density NT (Mg/m3)	Statistics (Bulk Density)	SOC CT (g/kg)	SOC NT (g/kg)	SOC CT (Mg/ha)	SOC NT (Mg/ha)	Statistic (SOC)
China					0-5	1.3	1.4	NT > CT	11.8	14	7.72	9.83	NT > CT
Du et al. (2010)					5-10	1.42	1.52	NT > CT	11.2	12	8.21	9.07	NT > CT
FD	536	Silt loam	7	Wheat-corn	10-20	1.51	1.61	NT > CT	11	9.1	16.69	15.32	CT > NT
					20-30	1.6	1.62	ns	7.5	7	12.18	11.34	ns
					30-40	1.6	1.58	ns	4	3.9	6.16	5.61	ns
					40-50	1.52	1.5	ns	4	4	5.73	5.8	ns
					0-50						59.69	56.96	ns
Spain				Wheat-chickpea	0-90	Measured but not reported by crop							ns
Lopez-Bellido et al. (2010)				Wheat-sunflower	0-90	Measured but not reported by crop							ns
FD	584	Clayey	20	Wheat-bare fallow	0-90	Measured but not reported by crop							ns
				Wheat-faba-bean	0-90	Measured but not reported by crop							NT > CT
				Continuous wheat	0-90	Measured but not reported by crop							NT > CT
Spain	430	Silt loam	17	Wheat-barley	10-20	1.38	1.53	NT > CT	5.9	5.4	8.169	8.288	ns
Plaza-Bonilla et al. (2010)					20-30	1.37	1.55	NT > CT	6.1	4.3	8.409	6.655	ns
FD					30-40	1.48	1.49	ns	5.7	3.6	8.481	5.429	ns
					0-40						33.94	34.63	ns
					0-5	1.2	1.16	ns	9.6	13.6	5.769	7.937	ns
					5-10	1.4	1.47	ns	8.3	6.9	5.78	5.069	ns
Spain	475	Loam	20	Wheat-barley	10-20	1.54	1.59	ns	6.5	4.9	10.048	7.849	ns
Plaza-Bonilla et al. (2010)					20-30	1.48	1.59	ns	5.1	4.8	7.599	7.545	ns
FD					30-40	1.53	1.59	ns	4.5	4.8	6.825	7.611	ns
					0-40						36.04	36.01	ns
					0-5	1.49	1.63	NT > CT			7.8	15.4	NT > CT
					5-10	1.57	1.67	NT > CT			8.1	11.6	NT > CT
Spain	428	Loamy sand	16	cheap pea-barley	10-20	1.68	1.58	CT > NT	not reported		16.2	14.3	ns
Lopez-Fando and Pardo (2011)					20-30	1.67	1.57	ns			14.3	11.1	CT < NT
ESM					0-30	1.61	1.62	ns			46.4	52.5	NT > CT
Spain	430	Loam	13	Barley	0-40	Measured but not reported by crop					46	49.9	NT > CT
Morell et al. (2011)													
ESM													
Spain	430	Loam	20	Wheat-vetch-pea	0-40	1.52	1.575	NT > CT	6.1	7.1	9.7	11.5	NT > CT
Hernanz et al. (2009)													
ESM													
Nebraska (USA)	708	Silty clay loam	19	Continuous corn, continuous soybean, and corn-soybean	0-150	1.47	1.45				131.61	171.22	NT > CT
Varvel and Wilhelm (2011)													
ESM	880	Loam	23	Continuous wheat	0-100	1.23	1.23	ns	11.3		128.3	124.7	ns
Kansas (USA)	580	Silt loam	45	Wheat-sorghum-fallow	0-100	1.62	1.66	ns	8.98		104.7	104.9	ns
Blanco-Canqui et al. (2011)													

ESM	440	Silt loam	21	Wheat-sorghum-fallow	0-100	1.42	1.40	ns	12.17		128.2	136.6	ns
China Lou et al. (2012) FD	450	Sandy loam	12	Continuous corn	20-40	1.43	1.44	ns	7.5	7.5	23.1	23.1	ns
					40-60	1.45	1.46	ns	6.5	6.3	19.5	18.8	ns
					60-80	1.5	1.52	ns	3	3.1	10.6	12	ns
					80-100	1.52	1.53	ns	2.5	2.6	8.8	9.9	ns
					0-100						87.6	93.1	NT > CT
					0-5	1.24	1.3	ns	11	13.5	6.9	9	NT > CT
					5-10	1.26	1.32	ns	10.6	10.6	6.8	7.1	ns
					10-20	1.42	1.34	ns	10.2	8	14.4	11.5	NT > CT
China Lou et al. (2012) FD	608	Loam	5	Continuous corn	20-40	1.42	1.45	ns	7.9	7.9	24.6	24.9	ns
					40-60	1.48	1.52	ns	7	7	20	20.7	ns
					60-80	1.6	1.55	ns	4	4	12.8	12.9	ns
					80-100	1.62	1.59	ns	3	3.1	9.8	10.1	ns
					0-100						95.4	96.3	ns
Brazil Boddey et al. (2010) ESM	1800	Clayey	15	3-yr rotation soybean/maize/barley with black oats and vetch	0-100	Not reported					55	58.8	NT > CT
Brazil Boddey et al. (2010)	1750	Clayey	17	Wheat-soybean	0-100	Measured but not reported for all sites					158.8	155	ns
	1750	Clayey	17	Maiz-wheat-soybean with black oat, black oat + vetch, and oil radish	0-100	Measured but not reported for all sites					163.5	172.3	NT > CT
Brazil Boddey et al. (2010) ESM	1850	Clayey	26	Maiz-wheat-soybean with black oat and oil radish	0-100	Measured but not reported for all sites					131.5	153.7	NT > CT
	1850	Clayey	26	Maiz-wheat-soybean with black oat and oil radish (The difference from the last experiment was the combination of crops within a rotation)	0-100	Measured but not reported for all sites					148.3	160.9	NT > CT

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