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Does conservation agriculture deliver climate change mitigation through soil carbon sequestration in tropical agro-ecosystems?

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ABSTRACT

Conservation agriculture (CA), comprising minimum soil disturbance, retention of crop residues and crop diversification, is widely promoted for reducing soil degradation and improving agricultural sustainability. It is also claimed to mitigate climate change through soil carbon sequestration: we conducted a meta-analysis of soil organic carbon (SOC) stock changes under CA practices in two tropical regions, the Indo-Gangetic Plains (IGP) and Sub-Saharan Africa (SSA), to quantify this. In IGP annual increases in SOC stock compared to conventional practice were between 0.16 and 0.49 Mg C ha^{-1} yr^{-1}. In SSA increases were between 0.28 and 0.96 Mg C ha^{-1} yr^{-1}, but with much greater variation and a significant number of cases with no measurable increase. Most reported SOC stock increases under CA are overestimates because of errors introduced by inappropriate soil sampling methodology. SOC increases require careful interpretation to assess whether or not they represent genuine climate change mitigation as opposed to redistribution of organic C within the landscape or soil profile. In smallholder farming in tropical regions social and economic barriers can greatly limit adoption of CA, further decreasing realistic mitigation potential. Comparison with the decreases in greenhouse gas emissions possible through improved management of nitrogen (N) fertilizer in regions such as IGP where N use is already high, suggests that this is a more effective and sustainable means of mitigating climate change. However the mitigation potential, and other benefits, from crop diversification are frequently overlooked when considering CA and warrant greater attention. Increases in SOC concentration (as opposed to stock) in near-surface soil from CA cause improvements in soil physical conditions; these are expected to contribute to increased sustainability and climate change adaptation, though not necessarily leading to consistently increased crop yields. CA should be promoted on the basis of these factors and any climate change mitigation regarded as an additional benefit, not a major policy driver for its adoption.

1. Introduction

Densely populated areas of South Asia and Sub-Saharan Africa (SSA) are especially vulnerable to climate change (Wheeler and von Braun, 2013; AGRA, 2014; Chattaraj et al., 2014) and are predicted to suffer crop yield decreases of at least 20% by 2050 with 40% and 30% risks of crop failure for maize and wheat, respectively, in a given season across large areas of Southern Africa (Lobell et al., 2008; Thornton et al., 2011; Cairns et al., 2013). It is therefore vitally important to develop strategies for sustainably increasing food production in these regions (Montpellier Panel, 2014). A group of crop management practices termed "conservation agriculture" (CA) are widely promoted to increase crop yields, reduce soil degradation and develop systems that are more resilient to weather-induced stresses including those caused by climate variability and change (FAO, 2001; Kassam et al., 2009; Thierfelder and Wall, 2010; Jat et al., 2012). Although CA shows great promise in many agro-ecological environments, there is continuing vigourous debate about its practical feasibility under certain farmer circumstances, especially for smallholders in mixed crop/livestock systems in tropical regions, where there is competition for crop residues between their use as animal feed

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as opposed to soil retention (Giller et al., 2009, 2011; Valbuena et al., 2012). There are also contrasting results from different regions and cropping situations regarding the impact of CA on crop yields (Rusinamhodzi et al., 2011; Baudron et al., 2012; Jat et al., 2012; Ngwira et al., 2012; Thierfelder and Wall, 2012; Thierfelder et al., 2013 a,b; Jat et al., 2014a,b; Pittelkow et al., 2015; Sommer et al., 2014; Vanlauwe et al., 2014; Aryal et al., 2015; Thierfelder et al., 2015).

In addition to discussion on impacts on crop yields, it is frequently claimed that CA mitigates climate change by sequestering organic C in soil (Hobbs and Govaerts, 2010; Jat et al., 2012; Lal, 2013, 2015; UNEP, 2013), though the experimental evidence for this is mixed and the topic has caused controversy (Powlson et al., 2014, 2015; Neufeldt et al., 2015).

CA comprises three principles, namely:

1. Zero or reduced tillage as opposed to inversion ploughing, thus minimising soil disturbance.
2. Maintenance of soil cover by retaining crop residues, as opposed to burning or removing them, or growing a green manure cover crop during periods when the soil would otherwise be bare.
3. Introduction of diversified and economically viable crop rotations instead of practicing monoculture.

The first aim of this paper is to quantify the impact of CA practices on soil organic C (SOC) stock through a meta-analysis of data from two tropical regions that are important for global food security, though for different reasons: the Indo-Gangetic Plains (IGP), the breadbasket of the most populous region in South Asia, and sub-Saharan Africa (SSA) where farmers' crop yields are generally very low and there is an urgent need to increase productivity, especially in the face of rapidly increasing population, depletion of soil fertility and likely decreasing yields through the impacts of climate change (AGRA, 2014). The second aim is to critically interpret the measured changes in soil C under CA practices to assess the extent to which they genuinely contribute to climate change mitigation as opposed to a redistribution of organic C within the landscape or soil profile; this aspect is lacking in many previous assessments. The third aim is to quantitatively compare any climate change benefits through soil C sequestration under CA with other mitigation measures such as improved management of nitrogen (N) fertilizers.

There is a dearth of data on soil C changes under CA in tropical regions. In the global meta-analysis of Govaerts et al. (2009), SOC stock in soil under CA was greater than in current conventional practice in 51% of cases but no different in 40%. However, of the 82 sites reviewed the vast majority were in North America with only 13% from tropical or sub-tropical regions. Mangalassery et al. (2015) reviewed published data on the impact of zero tillage (a key element of CA) on soil C but only 13 out of 49 datasets were from tropical regions: of those almost all were from Brazil or Mexico with, at most, only two relevant to smallholder farmers in SSA or South Asia.

2. Materials and methods

2.1. Data selection

A literature search was undertaken during 2014 (updated 31st March 2015), searching for keywords soil carbon; soil organic matter; conservation agriculture; zero tillage; reduced tillage; and either Indo-Gangetic Plains or Sub-Saharan Africa. In general only papers that included information on soil C stocks (as opposed to soil C concentration) were selected, though in some cases SOC stock could be calculated from the published data on SOC concentration and soil bulk density. In a few cases, where an experiment had continued for at least 5 years but the authors only quoted SOC concentrations, an assumed bulk density value (based on published bulk density data for similar soils in the region) was used to estimate stock; where this was done it is noted in Supplementary Table 1 or 2.

In each published study the additional SOC present after one of the CA practices compared to conventional practice was calculated and converted to an annual rate of increase expressed as Mg C ha^{-1} yr^{-1} to the soil depth specified in each paper. In the majority of cases the sampled depth was between 0.15 and 0.3 m and in a few cases 0.4 m. In the IGP there were four experiments with sampling to 0.6 m and one to 1.05 m and three sites in SSA where it was to 0.6 m; details are shown in Supplementary Tables 1 and 2.

2.2. Meta-analysis procedure

Meta-analysis was conducted on data from the SSA and IGP separately because of the very different soil types and cropping in the two regions: in IGP the majority of results were from experiments within the rice–wheat cropping system but in SSA most were from maize-based cropping and included both researcher-conducted experiments and measurements within farmers' fields. In many cases only one or two of the CA principles was applied so, in addition to conducting the meta-analyses using all data from a region, relevant sub-categories were also used. In the IGP three categories were selected: reduced tillage, residue retention, and crop diversification. In all cases in the IGP these practices were tested individually. In SSA almost all published data referred to combinations of treatments, with the following categories being used: reduced tillage, reduced tillage + residue retention, reduced tillage + residue retention + crop diversification,

Table 1
Summary of meta-analysis results for Indo-Gangetic Plains.

CA treatment	Annual rate of increase of SOC under CA treatment compared to conventional practice—predicted mean values from meta-analysis (Mg C ha^{-1} yr^{-1})	Number of studies	s.e.
All treatments	0.37	29	0.045
Specific treatment categories			
Reduced tillage (ZT)	0.49 (0.3)[a]	6	0.081
Residue retention (RR)	0.16	19	0.046
Crop diversification (D)	0.47	4	0.099
s.e.d. between treatments[b]	0.111		

s.e. and s.e.d. are standard error and standard error of difference respectively.
[a] The value of 0.3 Mg ha^{-1} yr^{-1} is considered more representative as it excludes 2 values from unusual situations that are much larger than all other data reviewed. See text for details.
[b] For comparisons between specific treatment categories, but not for comparison of specific treatments with 'all treatments' value.