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Limited potential of no-till agriculture for climate change mitigation

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The Emissions Gap Report 2013 from the United Nations Environment Programme restates the claim that changing to no-till practices in agriculture, as an alternative to conventional tillage, causes an accumulation of organic carbon in soil, thus mitigating climate change through carbon sequestration. But these claims ignore a large body of experimental evidence showing that the quantity of additional organic carbon in soil under no-till is relatively small: in large part apparent increases result from an altered depth distribution. The larger concentration near the surface in no-till is generally beneficial for soil properties that often, though not always, translate into improved crop growth. In many regions where no-till is practised it is common for soil to be cultivated conventionally every few years for a range of agronomic reasons, so any soil carbon benefit is then lost. We argue that no-till is beneficial for soil quality and adaptation of agriculture to climate change, but its role in mitigation is widely overstated.

The recent *Emissions Gap Report 2013*[1] makes bold statements about agriculture's potential to reduce greenhouse gas (GHG) emissions. The authors of the chapter on 'Policies for Reducing Emissions from Agriculture' estimate that at a marginal cost of less than US$50–100 per tonne of CO_2 equivalent (CO_2e), direct emissions from agriculture could be reduced by 1.1 to 4.3 Gt CO_2e yr^{-1} by 2020. They claim that 89% of this potential could be realized through improved management practices including conversion to no-tillage land preparation (Box 1), more efficient use of water and fertilizers and addition of biochar to soil.

Optimistic assessment

Overall the United Nations Environment Programme (UNEP) report[1] is helpful: it demonstrates that current global efforts to decrease emissions are far below what is necessary to avoid dangerous climate change[2] and it attempts to quantify opportunities for further reductions in different sectors. However, we have substantial concerns that the report overstates the potential for climate change mitigation in agriculture due to over-optimistic assumptions concerning the impact of no-till practices (Box 1 and Fig. 1).

There is abundant published evidence that no-till is beneficial for the functioning and quality of soil (Table 1) in many, though not all, situations[3–5]. The soil conditions developed offer potential for improved crop growth and increased resilience to weather variability and likely impacts of climate change, so in some environments can be regarded as a contribution to climate change adaptation. But published data on the magnitude of climate change mitigation from no-till through sequestration of organic carbon (C) in soil is much more equivocal, so the UNEP report[1] gives a false message of optimism regarding the ability of humanity to combat climate change by reducing GHG emissions from agriculture. If, as we maintain, the contribution through promoting no-till practices is substantially less than claimed, there is even more pressure to deliver mitigation through other approaches — both in agriculture and in other sectors.

Soil carbon stocks and climate change

Organic matter in the world's soils represents a major stock of organic C, storing about 1,500 Gt C (equivalent to 5,500 Gt CO_2) to a depth of 1 m and a further 900 Gt C in the next 1 m (refs 6,7). Organic C in the surface 1 m alone is three times the amount of C in atmospheric CO_2. Land-use changes — especially clearing of natural vegetation to expand the area used for crop production — have significantly depleted global soil C stocks and contributed to increased CO_2 emissions[8,9]. It is therefore entirely appropriate to consider opportunities to slow or reverse this trend through land-management practices. It has been estimated that a 10% increase in the global soil C stock would cancel out 30 years of anthropogenic CO_2 emissions[6,7]. But there are numerous reasons to be cautious about the potential for sequestering C in this way, including misunderstanding of C flows[10,11], limitations to the area of land that can be removed from agriculture[12] and the likelihood that organic C in soil will be subject to more rapid decomposition at elevated temperatures resulting from climate change[7,13].

Evidence from experiments and modelling

Several widely cited publications have alluded to the potential of reduced tillage to increase soil organic matter, sequester C, and so contribute to climate change mitigation[14–16]. There is certainly evidence that these practices often lead to some increase in organic matter (and hence C) concentration in the 15–20 cm layer of topsoil[17] and this has positive benefits such as reduced soil erosion and improved physical properties that increase the extent to which

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Box 1 | What is no-till?

No-till means reduced soil disturbance as an alternative to traditional cultivation by ploughing or discing, in which the soil is broken and then further cultivated to prepare a seedbed for planting crops. In large-scale mechanized farms tillage operations are performed with heavy machinery pulled by tractor; in smallholder agriculture in less developed regions it is generally achieved using a small animal-drawn implement, or hand-held tools. Where conventional cultivation is eliminated seeds are sown in a slot cut in the soil, causing minimum soil disturbance. Large-scale tractor drawn no-till seeders are widely used, but small-scale no-till seeders are increasingly available for use with either animal traction or small tractors. In Subsaharan Africa no till planting may also be achieved by making a hole for individual seeds, such as those of maize, with a 'dibble stick'. Although complete absence of tillage is called no-till or zero till, reduced tillage or minimum tillage practices are also used whereby there is an intermediate amount of soil disturbance. No-till and reduced till sometimes form a component of a suite of practices termed conservation agriculture (CA), comprising retention of crop residues on the soil surface and diversification of cropping systems in addition to reduced or no-till. Here we specifically address no-till agriculture rather than the complete CA package because this was the focus of the UNEP report with which we take issue, though in a few instances we refer to published data for the full set of CA practices where this is relevant or data is more readily available. For simplicity we use the term 'no-till' throughout to include the range of reduced till practices, from no-till to minimum till. The term 'conservation tillage' is used by some authors but we avoid this as it can be ambiguous, either meaning no-till/reduced till or, depending on the context, it may refer to the no-till component of CA.

Figure 1 | Mexican farmer practising no-till crop establishment. Photograph shows use of a 'swather' to cut crop residues and distribute them evenly over the surface of the undisturbed soil. Following this, seeds will be sown using a no-till seeding machine that cuts a slot for seeds, causing minimum disturbance of the soil.

soil can absorb rainfall and hold water, making it available for later crop use[5,18–20]. In some situations these soil improvements lead to increased crop yields[4,5]. But the opposite has also been observed, with decreased crop yields under no-till in cool moist climates[21] and in tropical environments, after heavy rains, the surface crop residues that accompany no-till in conservation agriculture can sometimes cause waterlogging and reduce yields[22].

So what is the evidence that soil organic carbon (SOC) stock increases substantially under no-till and can be viewed as C sequestration and hence a contribution to climate change mitigation? There have been several global reviews[6,17,23–25] with most of the experimental evidence derived from the Americas and Australia where no-till is widely practised on large, mechanized farms. A key issue is that much, though not all, of the apparent increase in SOC under no-till results from redistribution of C nearer to the soil surface and is therefore not a net increase in SOC stock[17,26–28]. A comparison of 69 sets of paired data for no-till and conventional till, where soil had been sampled to at least 40 cm depth, showed no overall increase in SOC stock under no-till: larger stocks in the surface 20 cm compared with conventional tillage were counteracted by smaller quantities in the 20–40 cm layer under no-till[17]. This altered depth distribution is illustrated in Fig. 2. In another global meta-analysis[23], SOC stock under conservation agriculture (combination of no-till and residue return — see Box 1) was greater than in conventional practice in about half of the cases but not different in 40%. Similarly, in a meta-analysis of experiments in Mediterranean climatic conditions[25] (mainly in the Mediterranean basin), it was found that no-till led to small increases in SOC stock of about 0.3–0.4 Mg C ha^{-1} yr^{-1}. In an experiment in northern France, one of the world's longest-running and closely-monitored experiments on tillage methods, no-till led to no increase in SOC stock in 41 years[29]. Thus the optimistic assertion in the UNEP[1] report, other claims or implications for major soil C gains through no-till[9,14,30,31] and in World Bank documents[32] are at variance with the conclusions from these detailed analyses of a large body of data.

A second issue results from confounding SOC mass versus concentration. In many studies only the concentration of SOC (expressed as % C or g C kg^{-1} soil) in specific soil layers is reported. For assessing the potential for climate change mitigation through C sequestration, it is necessary to express SOC as a mass or stock, expressed in units such as Mg C ha^{-1} or Gt C within a defined area. This approach requires measurement of soil bulk density in addition to SOC concentration, because bulk density is frequently altered by a change to no-till: crop residues are not mixed in the topsoil layer as occurs with ploughing or discing, so organic matter concentrates near the soil surface. This can lead to decreased soil density in the surface 5 cm compared with conventional tillage but much of the soil profile under no-till till almost invariably has increased bulk density due to the absence of disturbance. These trends are well established[33–35] but are often ignored in published literature comparing the effects of tillage methods on soil carbon stocks. Even when changes in bulk density are accounted for, the interplay of changed soil bulk density and the strongly developed SOC concentration gradient with depth under no-till leads to erroneous values for SOC stock if tilled and no-till soil are sampled to equal depth[36]. To obtain a valid comparison of SOC stocks, tilled and no-till soil should be sampled on an 'equal soil mass' basis instead of 'equal soil depth'[34,37]. Recently cited examples showed that an apparent increase in SOC stock when calculated on an equal depth basis can be decreased by 50% or eliminated completely if recalculated to an equal soil mass basis[37].

A third concern is that C sequestration in agricultural soil may not be long term. To qualify as climate change mitigation long term (more than 100 years) or permanent removal of CO_2 from the atmosphere is necessary. The extra carbon under no-till is predominantly in labile forms that would certainly be decomposed if no-till practices ceased and a farmer reverted to conventional tillage[38–40].

A more general limitation of climate change mitigation through soil C sequestration is that the soil's capacity to hold organic

C is finite. Soil organic carbon does not continue to increase indefinitely and annual rates of accumulation decline as the soil approaches a new equilibrium, which can take from 25 to 100+ years depending on climate and soil type[41–43]. Hence, rapid rates of SOC accumulation sometimes measured in the early years after a change in management, such as a shift to no-tillage, cannot be extrapolated indefinitely.

A new assessment but with many caveats

To assess the global potential for no-till practices to sequester soil carbon and thus mitigate climate change we take a value of 0.3 Mg C ha^{-1} yr^{-1} as an annual carbon accumulation rate under no-till, derived from the reviews cited above. We then apply this accumulation rate to the global area under cereal crops as these are the most likely systems where no-till can be practised. We exclude land in the Americas and Australia because no-till is already widely practised in these regions — where soils and climate are suitable — so any climate change mitigation is already accruing. Applying the value of 0.3 Mg C ha^{-1} yr^{-1} to the remaining global cereal crop area of 559 Mha (ref. 44) gives an annual global rate of SOC accumulation of 0.17 Gt C, equal to 0.6 Gt CO_2e. If the calculation is restricted to the areas under wheat, maize and rice (where no-till can be most easily practised, though with limitations for rice) the figure becomes 0.4 Gt CO_2e yr^{-1}.

Although these values for CO_2 mitigation are smaller than those proposed in the UNEP report[1] (1.1 to 4.3 Gt CO_2e yr^{-1}) they are of the same order so, superficially, could be taken as being in moderate agreement. However, we consider our estimate of 0.4 to 0.6 Gt CO_2e yr^{-1} to be highly optimistic for several reasons. First, the annual rate of accumulation we have used for SOC under no-till is probably too large. Although it approximates an average for those situations where increases were measured, there were many cases where the difference in SOC stock between no-till and conventional tillage was very small or zero[6,17,23,24,26,27,45]. Second, most of the reported differences will be overestimated due to the interplay of altered soil bulk density and the SOC gradient with depth in no-till as discussed above[36,37]. Third, in addition to the Americas and Australia, some form of reduced tillage is already used in substantial areas of cropland on large mechanized farms in Europe and Asia, so part of the 'potential' SOC gain from no-till is already occurring and cannot be counted as additional climate change mitigation. But there seems to be considerable uncertainty about the area now under no-till in large countries such as Russia, Kazakhstan, China and India[46]. Fourth, in some regions, such as northwest Europe, periodic ploughing is commonly practised to control the perennial weeds and soil compaction that are found to result from no-till in the soils and weather conditions of this region[42]. Periodic tillage also occurs in regions with wider adoption of no-till such as USA and Australia for a range of valid agronomic reasons[47,48]. Periodic cultivation will lead to considerable loss of any SOC accumulated in topsoil during the years of no-till[35,42,47,48] so the carbon sequestration and climate change mitigation benefits are lost or greatly reduced. Finally, there are significant barriers to widespread adoption of no-till by resource-poor smallholder farmers in less developed regions such as Subsaharan Africa and South Asia due to a range of economic, social and infrastructure factors that have been widely discussed elsewhere[4,5,49–51]. Thus, for all of these reasons, the apparent potential for increased global SOC stock from adopting no-till is unlikely to be realized.

In view of these major limitations and uncertainties regarding the impact and degree of adoption of no-till, we conclude that its global impact on soil C stocks will be only a fraction of the 0.4 to 0.6 Gt CO_2e yr^{-1} we estimate above, but we have insufficient information available to assess how small a fraction. It is possible that the total extra soil C accumulation could be close to zero. It is also known that a change to no-till can influence emissions of nitrous oxide, causing either increases or decreases[52,53]. As nitrous oxide is a

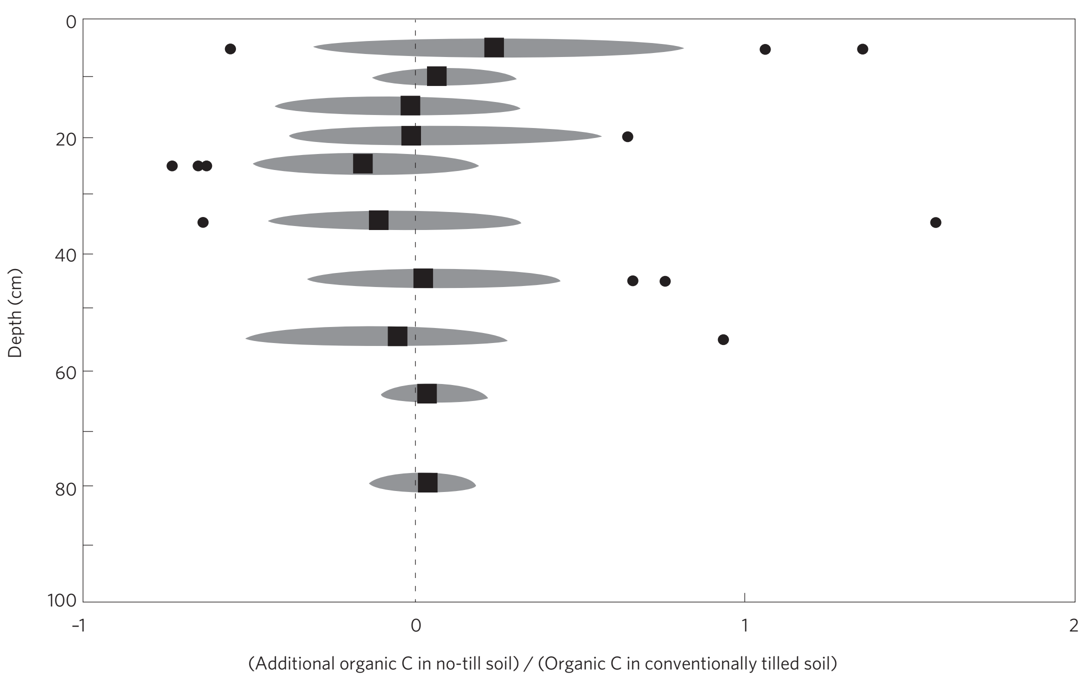

Figure 2 | Changes in soil organic carbon (SOC) content in soil under no-till compared to conventional tillage. Based on a meta-analysis of data from 43 sites where the two tillage systems had been applied for at least 5 years, and in many cases for more than 15 years. Large filled squares are the geometric mean of data in each soil depth; this value was used because the data were not normally distributed. Bars on each side of large squares represent the range of data from most studies. Values outside this range are shown by small points. An increase in SOC stock in no-till is indicated by an *x* axis value greater than 0. A value less than 0 indicates a decrease compared to conventional tillage. The data show an accumulation of organic C in the uppermost surface layers (0–10 cm) but a greater amount of C in conventional tillage at the base of the plough layer (about 25 cm). At greater depths there was no significant difference between tillage treatments. Redrawn from ref. 26.

Table 1 | Some key benefits and limitations or problems observed from a change to no-till cultivation practices.

Benefits	Potential problems/limitations
Soil properties, crop growth and environmental impacts	
Additional organic C in surface layer—beneficial for soil structure, soil biological activity and seedling emergence	Only small additional total organic C stock in whole soil profile—limited benefit for climate change mitigation
More continuous pores allowing increased rainfall infiltration — beneficial for water availability for crops and climate change adaptation	
Increased crop yields in some situations—probably owing to improved soil conditions and/or water availability	Crop yields decreased or unchanged in some situations, or increases only emerge after several years. Possibly associated with uneven seedling emergence or increased soil density causing inhibited root growth in some environments
Increased soil biological activity–especially if combined with crop residue retention	
Decreased risk of soil erosion—particularly if combined with crop residue retention	
	Nitrous oxide emissions may either increase or decrease—with negative or positive impacts on climate change mitigation
Farm operations	
Labour/time saved through elimination of tillage operations	May need extra labour or use of herbicides for weed control
Earlier sowing of crop often facilitated, leading to possibility of improved growth and yield in some environments	In wet climates delayed planting may occur owing to slower soil drying after rainfall events
Fuel saved through elimination of tillage operations—decreased costs and CO_2 emissions	
	Suitable machinery for planting may not be available, a particular issue for resource-poor farmers in less developed countries
Long-term increases in crop yields and farm incomes—especially if combined with crop residue retention and crop diversification	May be little or no increase in farm income in the short-term, a major limitation for small-holder farmers in less developed countries

potent GHG with a global warming potential 298 times that of CO_2 on a 100 year basis[54], even a small increase can easily outweigh the benefit of an increase in SOC. Short-term laboratory incubations of soils from tilled and no-till fields in the UK show there is a potential for the overall impact to be decreased emissions[55], but it is not known if this is realized under field conditions.

A regional assessment of the impact of a change to no-till was made for wheat-based production systems in the Indian states within the Indo-Gangetic Plain[56], the breadbasket of South Asia. IPCC methodology was used to estimate the potential for climate change mitigation through soil C sequestration, applying the IPCC factors to the different soils and climatic conditions in the region. This modelling study led to calculated annual rates of SOC accumulation under no-till in the range 0.2–0.4 Mg C ha^{-1}, broadly consistent with annual rates measured in other regions of the world and cited above[6,24]. The calculated annual rate of SOC accumulation in the entire region was less than 0.01 Gt CO_2e yr^{-1}, less than 1% of India's total annual GHG emissions. Another modelling study, in which two well-validated SOC models were applied to situations in Africa and South America[57], showed a smaller rate of SOC accumulation from no-till of only 0.04 Mg C ha^{-1} yr^{-1}. If this rate was reproduced globally, total soil C accumulation would be an order of magnitude less than our estimate.

Many assessments of potential climate change mitigation in agriculture rely on the estimate of 'global technical mitigation' by Smith *et al.*[15] of 5.5–6 Gt CO_2e yr^{-1}, with economic potentials in the range 1.5–4.3 Gt CO_2e yr^{-1} depending on the assumed carbon price. These values can be misunderstood to imply a very large mitigation potential within cropped land. In fact 36% of the total estimate is from the restoration of degraded land to its natural state and re-flooding of organic soils that are now under cultivation. Although re-flooding of organic soils is desirable for carbon sequestration, it is only likely to be practicable on small areas and the area of productive land that could be removed from agricultural production is limited as it represents a trade-off against the goal of global food security[58,59]. A further 28% of the total estimate refers to management of grazing land and improved management of livestock and manure to decrease emissions of nitrous oxide and methane. The mean values for annual accumulation of SOC from a combination of reduced tillage and return of crop residues cited in Smith *et al.*[15] are in the range 0.04 to 0.19 Mg C ha^{-1} yr^{-1}, depending on climate zone, rather less than the value of 0.3 Mg C ha^{-1} yr^{-1} we used in our assessment above and again indicating that our estimate is highly optimistic.

It is noteworthy that the estimates of soil C increases under no-till used in the UNEP report rely heavily on Derpsch *et al.*[46]. However this reference contains virtually no data on SOC, being mainly concerned with the areas under no tillage in different regions of the world and opinions, not measured data, about the potential impacts on soil carbon. The UNEP report[1] is also at variance with the more balanced view of the benefits and limitations of conservation agriculture (including no-till) expressed by 43 scientists with detailed knowledge of the topic in the "Nebraska Declaration"[60].

Conclusions

The claims made for climate change mitigation through conversion to no-till agriculture in the chapter 'Policies for Reducing Emissions from Agriculture' in the 2013 UNEP report[1] are unrealistic and not based on thorough review of the scientific literature. Although the authors mention the social, economic and infrastructural barriers to adoption of no-till, especially for smallholder farmers, they proceed to ignore these in making their assessment. This leads to overstatement of the global potential for soil C sequestration. There are some genuine opportunities for mitigating climate change in the agricultural sector, largely through improved management of water and nutrients — especially nitrogen from fertilizer[61,62] and manure[63,64] — and through improved feeding practices and management of ruminant livestock[15,65,66].

Reduced tillage does lead to a reduction in GHG emissions associated with tillage operations, whether CO_2 from burning tractor fuel in mechanized agriculture[67,68] or production of feed required for draught animals in smallholder systems[69]. In the case of fuel use in mechanized agriculture, although this saving is beneficial for climate change mitigation, a study from the central USA indicates that its magnitude is small relative to possible changes in N_2O emissions[68]. For conditions in the USA, total GHG emissions associated with growing non-legume crops (maize, wheat) are dominated by those from the production and use of agricultural lime and nitrogen fertilizer[67]. Therefore although the emissions saving from reduced use of fuel are significant and beneficial[70], a 'whole system' approach emphasizes the great importance and potential of achieving improved efficiency in the use of nitrogen fertilizer for climate change mitigation in agriculture.

Reduced tillage certainly has a role to play as one of the strategies contributing to global food security and the protection of soils, and thus to climate change adaptation through building agricultural systems that are more resilient to climate and weather variability. In regions where no-till or reduced tillage is appropriate it should be promoted on these grounds, but not on the basis of equivocal evidence for climate change mitigation. No-till agriculture can deliver significant benefits for farmers and sustainability in many (though not all) situations (Table 1): reduced GHG emissions are a small but important additional benefit, not the key policy driver for its adoption.

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Competing financial interests
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