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SYNTHESIS AND EMERGING IDEAS

Carbon input differences as the main factor explaining the variability in soil organic C storage in no-tilled compared to inversion tilled agrosystems

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Abstract Conversion to no-till (NT) is usually associated to increased soil organic carbon (SOC) stocks in comparison to inversion tillage (IT). However, an important and unexplained variability in the changes in SOC with NT adoption exists, which impedes accurate prediction of its potential for C sequestration. We performed a meta-analysis with pedo-climatic and crop factors observed to influence SOC storage under NT at local and regional scales, in order to determine those better explaining this variability at a global scale. We studied SOC stocks (0–30 cm) in an equivalent soil mass, climatic and soil characteristics in 92 NT–IT paired cases. A sub-base with the 35 pairs providing C inputs was used to test their effect. Greater SOC stocks were observed with NT, with a smaller difference than often described (6.7%, i.e. 3.4 Mg C ha^{-1}). Crop C inputs differences was the only factor significantly and positively related to SOC stock differences between NT and IT, explaining 30% of their variability. The variability in SOC storage induced by NT conversion seems largely related to the variability of the crop production response. Changes at the agro-ecosystem level, not only in soil, should be considered when assessing the potential of NT for C sequestration.

Keywords No-tillage · C sequestration · Crop primary production · Soil C · C sinks

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Introduction

The implementation of no-till (NT) techniques on agricultural fields is increasing worldwide, and it has been demonstrated to imply important economical and environmental advantages (Liebig et al. 2004; Wienhold et al. 2004). No-till systems have also been observed to favour the accumulation of organic C in the soil in many cases (e.g. Kern and Johnson 1993; West and Post 2002; Lal 2004). This led to consider NT as a possible tool to help mitigating the atmospheric CO_2 concentration increase.

However, the effectiveness of NT to sequester additional soil organic C (SOC) in comparison to the so-called "conventional" tillage (CT) is controversial, and a large discrepancy between estimations of SOC storage induced by NT implementation can be seen in the literature (e.g. Àlvarez et al. 1998; VandenBygaart et al. 2003; Gregorich et al. 2005; Liebig et al. 2005; Puget and Lal 2005; Zinn et al. 2005). This controversy arises in part from the fact that the methodological framework is not homogeneous among the different studies conducted to evaluate the soil C enrichment under NT. For instance, Baker et al. (2007), Blanco-Canqui and Lal (2008), Angers and Eriksen-Hamel (2008) or D'Haene et al. (2009) showed that the soil depth considered for quantifying SOC stocks under NT and CT can determine the final SOC balance between treatments, resulting in more or less SOC under NT in comparison to CT if only surface layers or deeper ones are considered. Also, comparisons can be biased when done for standardized soil depths, instead than for an equivalent soil mass (Ellert and Bettany 1995). In addition, there is a large variability within the agricultural techniques described as CT in different areas and studies, which implies that the studies comparing C stocks under NT and CT in the literature are not necessarily comparable.

However, even when attention is paid to these potential methodological biases, the large and unexplained discrepancy of SOC stock responses to NT conversion remains (e.g. Angers and Eriksen-Hamel 2008). This implies, first, that the extrapolation of published storage values for a given situation to estimate SOC storage expected from land conversion to NT at larger scales is very risky, and, second, that the capacity of NT systems to sequester SOC is quite dependent on site-specific pedo-climatic conditions (Puget and Lal 2005). A better understanding of the factors influencing the soil ability to store C under NT is therefore needed for accurate predictions of soil C response to NT conversion. This would also allow for a better selection of the soils in which NT is to be implemented for the purposes of greenhouse mitigation, choosing in priority the soils with high C storage potential under NT better than those that are expected to remain unchanged or to lose C under NT.

Soil C vulnerability in systems including regular tillage and its response to the implementation of NT are have been shown to be influenced by pedo-climatic conditions in several site- and regional-scale studies (e.g. Carter 1994; McConkey et al. 2003; Franzluebbers 2005). Soil texture is an important factor controlling the stabilization of SOC both by adsorption to the mineral fraction and by entrapment within stable aggregates (Six et al. 2002; McConkey et al. 2003). Climate can also impose constraints on the processes that regulate SOC dynamics in regularly tilled soils, resulting in different efficiencies of the change to NT for SOC sequestration in tropical than temperate areas, and in dry and humid regions (Ogle et al. 2005).

Another important fact in relation to differences observed in the C cycle between NT and CT systems is that, for a given cropping system, the crops primary production can differ between NT and CT plots, resulting in different C inputs to the soil following conversion from CT to NT. Several authors have described increased crop production under NT (e.g. Olson and Ebelhar 2009; So et al. 2009), but a number of studies revealed that conversion to NT can have no effect or even reduce crop production compared to continuing CT (Riley et al. 1994; DeFelice et al. 2006; Wang et al. 2006; Giller et al. 2009). SOC stock could therefore increase under NT where NT promotes higher crop production. This idea has been proposed in a number of case studies (Campbell et al. 1996; Black and Tanaka 1997; Follett et al. 2005), but not investigated on a large dataset.

The objective of this study is gaining knowledge on the effect of the conversion of regularly tilled soils to NT on soil C storage by analyzing the large and unexplained variability reported for this storage in the literature. We critically reviewed the existing literature on the effect on SOC stocks of NT conversion of previously tilled soils in relation to continuous CT, in order to create a database from which a meta-analysis would be run to evaluate the factors affecting the storage of SOC under NT compared to the tilled systems with crop residue incorporation through inversion tillage (IT).

Materials and methods

Selection of studies and SOC stocks calculation

A survey of the literature comparing C stocks under NT and CT was conducted using ISI Web of Knowledge^{SM}. An accurate assessment of the potential of NT for increasing SOC stocks needs an accurate selection of data, in order to avoid methodological biases. For the establishment of the database we only considered studies published until December 2009 and meeting the following criteria: Situations (i) displaying more than 5 years since the conversion to NT (to avoid comparing situations in the initial stages of changes in C dynamics (Causarano et al. 2008)), (ii) where NT meant direct seeding (situations of minimum or reduced tillage were excluded) with crop residues left on the soil surface and CT meant mouldboard ploughing or full inversion tillage (IT) that incorporates crop residues into the soil and leaves less than 30% of residue cover after tillage, (iii) with similar agricultural history until the implementation of NT, and (iv) with equal cropping systems (rotation, fertilization, etc.) in the plots under NT and IT. For each of the selected studies, when data of SOC stocks under NT and IT where given for different N doses, crop rotations, or other cropping treatments, IT–NT pairs for each of the described treatments were included in our database. For studies providing data for different replicates, or from replicated trials, we used the average values. Otherwise, data were used as provided by the authors. Data from studies including practices interfering with the C cycle, such as burning, were not considered.

Among the selected studies, only C stocks in the 0–30 cm were considered. Studies providing SOC data referring to less than 30 cm depth were excluded. Angers and Eriksen-Hamel (2008) recently suggested considering at least the upper 40 cm of the soil. Reality is that most of the studies found in the literature do not provide data below 30 cm. Since 30 cm is equal or deeper than the tilled depth, we set the limit at 30 cm for selecting studies for our database. In two cases (Deen and Kataki 2003; Sa et al. 2001) where data were reported for the 20–40 cm depth increment, the stock for the 20–30 increment was calculated assuming homogeneity of the 20–40 cm layer.

Finally, SOC data were expressed for equivalent soil masses. If not presented as such in the study, we calculated SOC for equivalent masses from bulk density and SOC concentration data (Ellert and Bettany 1995). The reference mass was considered to be that of the most compacted treatment at each site. The needed amount of soil mass to be added in order to reach the reference mass in the other treatments at the same site was calculated, and the amount of SOC that this extra mass included was added. The bulk density and SOC contents used to calculate the quantity of soil mass to add, and the amount of SOC that this addition implied, were calculated from data of the immediate below layer, when available. If not, data from the immediate above layer were used. When data of SOC were reported for a soil volume (Mg ha^{-1}), and no data of bulk density were reported by the authors (as in Carter 2005; Wanniarachchi et al. 1999), we assumed that they were no differences in bulk density between NT and IT.

From SOC stock data in the NT–IT pairs in our database we calculated the relative (*SOCrel*) and absolute (*SOCabs*) difference in stock under NT and IT as follows:

$$SOCrel = (\text{SOC stock NT} - \text{SOC stock IT}) / \text{SOC stock IT}$$

$$SOCabs = (\text{SOC stock NT} - \text{SOC stock IT})$$

Pedo-climatic factors

Soil texture, which was given in every study (sand, silt and clay contents or category in the USDA texture triangle) and assumed herein to be equal for NT and IT at each site, was selected as soil factor. When the category in the USDA texture triangle was reported, the mean clay, silt and sand values of the texture triangle category were attributed to the considered soil. If the sand, silt and clay contents were reported, these values were used. A cluster analysis on the sand, silt and clay contents was then performed using the "hclust" R procedure. It generated four different classes. The four classes corresponded to soils containing (i) more than 50% sand; (ii) more than 33% clay and less than 40% silt; (iii) less than 25% clay, less than 50% silt and less than 50% sand; and (iv) more than 50% silt. These four classes are thereafter called *sand*, *clay*, *silt loam* and *silt*, respectively.

Climatic characteristics of sites presenting a NT–IT pair meeting the criteria were compiled. We selected three climatic factors: mean annual temperature (T), mean annual precipitation (P) and aridity index (P-to-ETP ratio) as used in Franzluebbers and Steiner (2002). When not provided in the study, P and T data were compiled from the US National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html) for the US sites and from a general data base (http://www.worldclimate.com/) for sites located elsewhere. Mean annual ETP was calculated using the method of Thornthwaite from monthly average temperature data for all locations in the dataset. In two cases (Follett et al. 2005; Du et al. 2010) NT–IT pairs from irrigated fields were included. Since authors described the average irrigation doses applied, we added these amounts of water to average natural precipitation in order to correctly assess both P and the aridity index.

When studying the dataset, we observed that more than one-third of the studies were located in NW USA, with as a consequence an over-representation of the climatic characteristics of this area in the dataset. To evaluate this possible bias, we averaged comparisons for each site, and run the analysis for climate parameters both on the obtained means and in the whole original dataset.

Estimation of potential C inputs

Where possible, the yearly difference of C inputs (DI) between NT and IT plots were estimated. Similarly to SOC stock differences, relative (*DIrel*) and absolute (*DIabs*) C input differences were calculated as follows:

$$DIrel = (\text{yearly C inputs under NT} - \text{yearly C inputs under IT})/\text{yearly C inputs under IT}$$

$$DIabs = (\text{yearly C inputs under NT} - \text{yearly C inputs under IT})$$

When total C inputs were estimated or measured by the authors, these values were used. However, in most cases, only aboveground residue production or crop yields were indicated. If aboveground crop residue inputs were indicated, we calculated the DI indicators by replacing C inputs by aboveground C inputs. In this case, it was therefore considered that the ratios “C inputs in aerial residues in the NT plots-to-C inputs in aerial residues in the IT plots” and “C inputs in root residues in the NT plots-to-C inputs in root residues in the IT plots” are equal. If crop yields were indicated, crop residues were estimated from the crop yields according to the harvest indexes provided by Sisti et al. (2004). When crop residues or crop yields were reported in mass of dry matter per hectare, they were converted in mass of C per hectare, assuming an average 42% C content. In the case of rotations including more than one crop or periods of fallow, the weighed average annual inputs (in Mg C ha^{-1} $year^{-1}$) were calculated as a weighed average, considering the time under each crop for the entire rotation.

The whole database presenting SOC stocks, mean annual temperature, mean annual precipitation, aridity, texture classes, yearly C inputs and experiment durations is presented in Appendix A.

Statistics

All statistical analyses were performed using R. The effect of tillage on SOC stocks in the 0–30 cm was tested using a pairwise *t*-test. Several studies met the required criteria, but did not provide any indication on crop residue production or crop yields. Therefore, we distinguished two databases for the analyses. The first one contained SOC stocks, texture and climatic variables and the second one, which was three times smaller, contained situations where SOC stocks, texture, climatic variables and DI values were available. Herein, these databases will be named large and reduced, respectively. The effects of the factors were investigated using multiple linear regressions. As indicated above, texture data were categorized based on clay, silt and sand contents using cluster analysis. The climatic variable(s) introduced in the models were annual precipitation and mean annual temperature or aridity as aridity is obviously linked with precipitation and temperature. As some studies provided several paired data, these could not be considered as independent. This was handled by considering the study where the data came from as a random effect. The multiple regressions were therefore conducted using the R “lme” procedure.

The following mixed models were tested to try to explain relative and absolute C stock differences:

(i) texture, aridity and their interaction;
(ii) texture, mean temperature, annual precipitation and their interactions on the large database.

(iii) DI (relative and absolute), texture, aridity and their interactions;
(iv) DI (absolute and relative), texture, mean annual temperature, annual precipitation and interactions on the reduced database.

Due to the structure of the dataset, it was not possible to test all interactions in the model (iv). Consequently, only the simple effects and the two-ways interactions except one (5 over 6) were tested (we made the analyses with each one of the interactions removed to check that the results did not depend on which interaction was removed). We also checked that the results obtained on the large database were conserved when the analyses (i) and (ii) were performed on the reduced database.

Similarly, two mixed models were tested to try to explain the input differences between NT and IT systems:

(v) texture, aridity and their interaction;
(vi) texture, mean temperature, annual precipitation and their interactions.

As some degrees of freedom were lacking to test all interactions in the model (vi), only the two-ways interactions were tested.

Results

Database description

The database (Appendix A) comprised 92 NT–IT paired situations from 37 studies. It covers a large range of mean annual temperatures (from 5.2 to 20.6°C), annual precipitation (from 390 to 1,690 mm year^{-1}) and aridity. The large database contained 11, 25, 21 and 35 paired situations on soils classified as *sand*, *clay*, *silt loam* and *silt* respectively. Since study inclusion was based on availability and data appropriateness, different regions were unequally represented in the database. Most of the studies are from North America and Europe. Central and South America are less represented in the database, and information from the other continents is scarce (Asia) or lacking (Africa). Thirty-five pairs (from 14 different studies) included information on C inputs to the soil, or crop yields, and constituted the reduced database.

Influence of NT conversion and NT conversion on C stocks in the 0–30 cm

NT treatment significantly increased C stocks in the 0–30 cm ($n = 92$; $t = 2.822$; $p = 0.006$). This increase was equal to about 6.7% of the stock under IT on average and was very variable (standard deviation = 17%). In absolute value, NT conversion induced an extra storage of 3.4 Mg C ha^{-1} on average.

Influence of pedo-climatic factors on SOC stock differences between NT and IT plots

Relative SOC stock differences as a function of annual precipitation, mean annual temperature, aridity and texture class are represented in Fig. 1. There was neither an effect of aridity nor an effect of texture on SOC stock differences between NT and IT. When the analysis was conducted with mean annual temperature and annual precipitation instead of aridity, no significant effect was observed either. No significant influence of pedo-climatic factors was observed when the analyses were conducted on the absolute SOC stock differences. These results were valid also when comparisons were done considering the mean climatic values of for each geographical location. The ANOVA tables are available as supplementary data (Appendix B).

Influence of C input differences on SOC stock differences between NT and IT plots

The C inputs under NT and IT were estimated when it was possible, that is, for 35 pairs out of a total of 92. As for the large database, no effect of pedo-climatic factors on SOC stock differences was observed in this subset of studies (see supporting information for ANOVA tables). On the contrary, there was a very significant effect of the relative yearly difference of inputs (*DIrel*) between NT and IT on relative SOC stocks difference under NT and IT ($p = 0.01$). This effect was the same when the analysis was conducted with aridity or mean temperature and annual precipitation instead. As in the previous analyses conducted in the large or the reduced database without *DIrel* in the model, the pedo-climatic factors did not have any significant effect on the difference of C stocks between NT and IT. Similarly, the yearly absolute

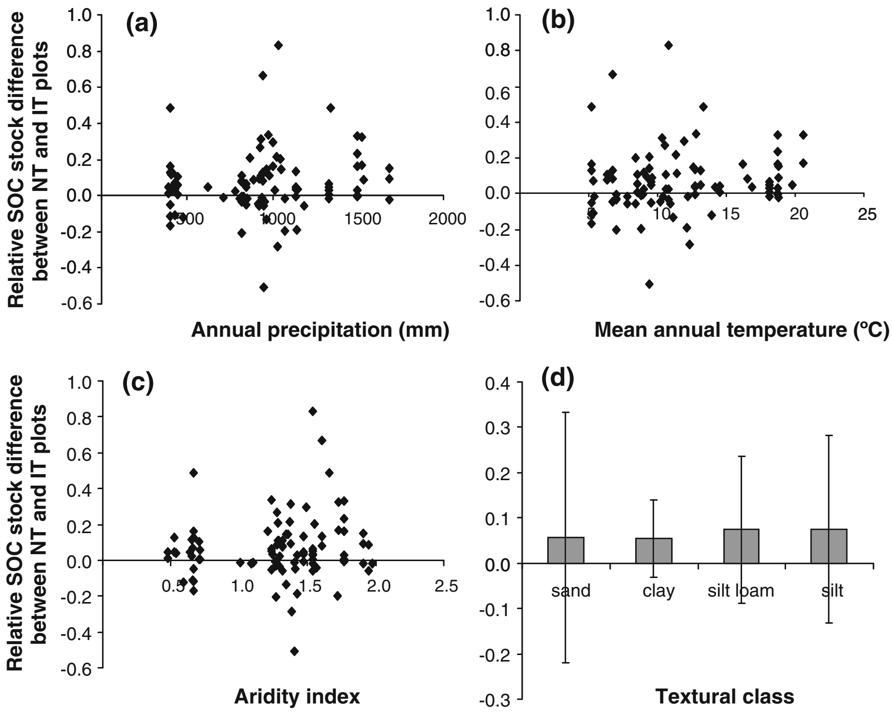

Fig. 1 Relative SOC stock difference as a function of annual precipitation (**a**), mean annual temperature (**b**), aridity index (**c**) and texture (**d**). None of these factors is significantly correlated with relative SOC stock difference

C input difference had a significant ($p = 0.04$) effect on the absolute SOC stock differences. The ANOVA tables are available in Appendix B.

DIrel is plotted against relative difference on C stocks in Fig. 2. In the dataset, there were as many pairs showing C inputs increase as pairs reporting C inputs decrease under NT. As observed in the previous models with texture and climatic factors on top of *DIrel*, there was a very significant positive relationship ($n = 35,\ t = 3.773;\ p < 0.001,\ r^2 = 0.30$) between the relative difference of inputs and the relative difference of C stocks in IT and NT systems. This relationship explained 30% of the variance of relative SOC stock differences. The intercept was positive (0.041 ± 0.019) and significantly different from 0 ($n = 35,\ t = 2.133;\ p = 0.04$), indicating that for equal inputs SOC stock is higher under NT compared to IT. It is also noticeable that for any given site or case-study, when an increase of inputs under NT was reported, it led systematically to increased or equivalent SOC storage (e.g. Hernanz et al. 2002). On the contrary, when C inputs were smaller under NT, SOC storage was reduced or increased depending on the study.

Texture and climatic factors and the difference of inputs between NT and IT systems

Results described above showed that the factor best associated to an increment in SOC stocks under NT is increased C inputs. Therefore, we searched for

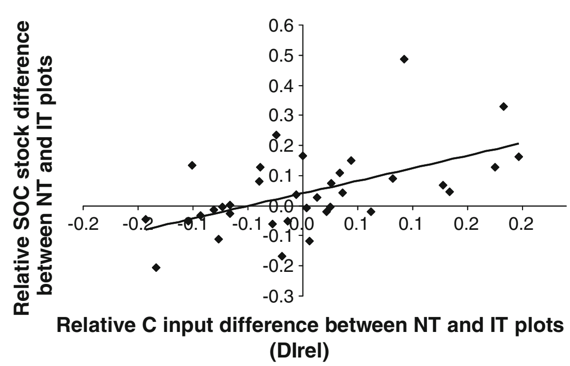

Fig. 2 Relative SOC stock differences plotted against relative yearly C input differences between NT and IT plots. Relative SOC stock differences and *DIrel* are very significantly correlated ($n = 35,\ t = 3.5983.773;\ p \leq 0.001,\ r^2 = 0.30$) and the intercept is significantly different from 0 ($n = 35$, $t = 2.133;\ p = 0.04$)

correlations of such increase of inputs under NT with texture or climatic variables. No effect of both texture and climatic variables on the yearly difference of C inputs was observed in this dataset. The ANOVA tables are available as supplementary data (Appendix B).

Discussion

As expected, we observed a large variability in SOC storage induced by NT implementation and NT was found to increase significantly SOC stocks by approximately 6.7%, corresponding to an average extra storage of 3.4 Mg C ha^{-1}. This is in the same order of magnitude, but below the 4.9 Mg C ha^{-1} found by Angers and Eriksen-Hamel (2008) in a recent review. West and Post (2002), in their review of cases worldwide, gave also a mean value of 0.57 Mg C ha^{-1} per year, which means 8.5 Mg C ha^{-1} for plots with 15 years under NT, as is the average of our large database. Considering some regional-scale reviews, the average data found in our database was below the 5.6 Mg C ha^{-1} found by Johnson et al. (2005) for Central USA, and similar to the average difference of 3.3 Mg C ha^{-1} in 10 ± 5 years found by Franzluebbers (2005) for SE USA. Our data were also close to those reported in France (0.20 ± 0.13 Mg C ha^{-1} per year, which makes 3.0 Mg C ha^{-1} in 15 years (Arrouays et al. 2002)). These results illustrate the variability found in the literature. The lower value of SOC storage found in the present study in comparison to others can be explained obviously by the difference in the databases, but also by the fact that we calculated SOC stocks on an equivalent mass basis. As NT soil profiles are usually denser than tilled ones, working on an equivalent mass basis tends to lower the difference of SOC stocks between tilled and NT plots (Ellert and Bettany 1995; Wander et al. 1998; Puget and Lal 2005). Moreover, SOC stock data included in our database corresponded to soil depths of 0–30 cm. Interestingly, data given in Johnson et al. (2005) and Franzluebbers (2005) are reduced to 4.7 and 2.9 Mg C ha^{-1}, respectively, when only studies giving data for this depth are considered. This illustrates the importance of considering at least the entire tilled depth in this type of studies, as recently demonstrated by Angers and Eriksen-Hamel (2008) and D'Haene et al. (2009). Studies providing data beyond this depth could be of great value in this sense, and are scarce in the literature.

The general idea is that, under NT, SOC stocks increase because of less mineralization. In this study, the only factor explaining the influence of NT on C stocks at a global scale was the difference of C inputs, which explained 30% of the observed relative differences in SOC stocks between NT and IT. Higher C inputs usually result in higher C stocks. Our results show that this general rule for soils works for NT–IT systems as well. The idea that higher stocks under NT can be due to higher inputs has been suggested in some case-studies (Campbell et al. 1996; Black and Tanaka 1997), and some regional-scale studies (Franzluebbers 2005; Johnson et al. 2005; Liebig et al. 2005), and is demonstrated here for the first time at a large scale with an appropriate dataset. Another interesting fact of this relationship is that the intercept was significantly above 0 (Fig. 2). This means that NT systems would intrinsically tend to store more SOC than IT. The value of this intercept was low and the uncertainty associated to this value was high, which makes further studies providing C inputs data especially necessary to confirm this aspect.

Although in regional-scale studies, pedo-climatic factors such as soil texture (Zinn et al. 2005) or aridity (Franzluebbers and Steiner 2002) have been shown to influence the effect of land conversion to NT on SOC storage, the absence of effects of the investigated pedo-climatic factors on SOC storage under NT in our database suggests that these relationships are not a general feature when a larger dataset is considered. For instance, contrary to Zinn et al. (2005) who considered that NT would have a higher positive impact in C stocks in Brazilian sandy soils, we observed no effect of soil texture in the large database ($n = 92$). Similarly, contrary to deductions by Franzluebbers and Steiner (2002) for SE USA, it seems that aridity, as estimated through the P-to-ETP ratio, does not influence the impact of NT on C stocks when the relationship is investigated at a larger scale and NT–IT pairs are selected following criteria as the ones given here.

In this study, the analysis of the influence of C inputs had to be conducted on a reduced database because about two-thirds of the cases comparing C stocks under tilled and NT systems did not give any information on the inputs. Putting together these 35 pairs showed that C input differences are crucial to explain C stock differences between NT and IT systems. Still, very few of this studies reported data on total above- and below-ground biomass production under NT and IT, and so that, we made the assumption that no differences in the proportion of aerial and subterranean growth of crops existed between NT and IT plots at each site. This implies that further studies comparing the effect of IT and NT on soil properties, and especially on organic C dynamics and storage, should include information on the difference of C inputs between the two systems.

This work shows that the best way to store C using NT is to implement it in areas or within agrosystems in which increased C inputs can be achieved under NT compared to IT systems. To sequester C using NT, one should therefore find situations where NT conversion helps a given cropping system to increase productivity in comparison to continuous IT. Unfortunately, the present dataset does not give any ideas on how to find such win–win situations. Indeed, neither texture nor climatic variables were correlated with input differences.

Some interactions of the suppression of tillage with other parameters of the cropping system resulting in increased productivity under NT than under IT can be, however, found in our dataset, although no clear trends appear. For instance, Black and Tanaka (1997) and Halvorson et al. (2002) found a shift from less crop biomass production under NT to more production under NT in comparison to IT when fallow was excluded from the rotation. This shift was followed by a change from smaller SOC stocks under NT to greater stocks under NT in comparison to IT. Follett et al. (2005) found that changing N doses created different crop-residue C balances between NT and IT. However, the main factor affecting SOC sequestration under NT in comparison to IT in their study on a Mexican Vertisol was the presence of a legume in the rotation. In a semiarid Mediterranean soil, however, Hernanz et al. (2002) found no effect of including a legume in the differences neither in crop yields nor in SOC stocks under NT and IT. It thus appears at this stage that there is not a universal cropping system that can guarantee higher crop yields and more SOC stock under NT in comparison to IT. This is so because the change in soil conditions when NT is implemented can have different consequences for crops development depending on soil, crops and climate. For instance, more soil water storage under NT can enhance crop yields in dry areas (Bescansa et al. 2006), but can also lead to waterlogging problems and delayed seeding of cereals in more humid areas and/or more clayey soils (e.g. Angers et al. 1997; Alakukku et al. 2010). Similarly, germination and emergence of crops can be affected by soil temperature, which can be lower under NT than with IT if more water is stored in NT. More research on the cropping parameters that might favour SOC accumulation when implementing NT is also needed if promotion of NT is considered under the perspective SOC sequestration.

This study presents a first explanation at a large scale for the observed variability of SOC storage induced by NT. However, an important part of this variability remains unexplained. Indeed, only 30% of the variance of relative SOC stock differences was explained by input differences. This suggests that (i) some important explanatory factors are missing or (ii) the relevant factors were considered but they need to be used differently. First, management practices such as fertilization (Gregorich et al. 2005), the cropping intensity (Peterson et al. 1998) or crop types (VandenBygaart et al. 2003) can influence the effectiveness of NT for sequestering extra SOC. These two factors were not included in our study because fertilization doses were poorly documented in most studies and there were so many different crop rotations that this information was difficult to use. Similarly, the effect of different erosion rates in IT plots in comparison to NT plots for a given site and management might result in smaller SOC stocks in IT, even with similar or higher C inputs in IT plots. This effect was not included either in our dataset because no relevant information was provided by any of the selected studies. Second, it is likely that some climatic phenomena influencing C storage under NT cannot be correctly picked with annual means. For instance, aridity or temperature and their interactions with other factors could need to be taken into account at a much finer time-scale. Such precision was not the objective of this work and cannot be achieved without using simulation models. Very well documented long-term sites with IT and NT paired plots would be needed for such a likely fruitful approach.

In summary, our findings mean that C input differences are a major factor explaining the variability in SOC storage in the tilled layer following NT conversion. A better understanding of the role of C inputs needs more information on (i) crop production modifications induced by NT implementation, including both the aerial and subterranean parts of crops, (ii) of the effects of C inputs on SOC storage in both surface and deep soil layers under NT, and (iii) on the possible interactions of the suppression of tillage with other parameters of the cropping system. Getting this information is crucial now for better estimates of SOC stock differences induced by NT. These results also mean that SOC storage under NT should be considered necessarily at the agro-ecosystem level rather than at the soil level only.

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References

Alakukku L, Ristolainen A, Sarikka I, Hurme T (2010) Surface water ponding on clayey soils managed by conventional and conservation tillage in boreal conditions. Agric Food Sci 19:313–326

Àlvarez R, Russo ME, Prystupa P, Scheiner JD, Blotta L (1998) Soil carbon pools under conventional and no-tillage systems in the Argentine rolling pampa. Agron J 90:138–143

Angers DA, Eriksen-Hamel NS (2008) Full-inversion tillage and organic carbon distribution in soil profiles: a meta-analysis. Soil Sci Soc Am J 72:1370–1374

Angers DA, Bolinder MA, Carter MR, Gregorich EG, Drury CF, Liang BC, Voroney RP, Simard RR, Donald RG, Beyaert RP, Martel J (1997) Impact of tillage practices on organic carbon and nitrogen storage in cool, humid soils of eastern Canada. Soil Tillage Res 41:191–201

Arrouays D, Balesdent J, Germon GC, Jayet PA, Soussana JF, Stengel P (2002) Contribution à la lutte contre l'effet de serre. Stocker du carbone dans les sols agricoles de France? Expertise Scientifique Collective, Synthèse du rapport. INRA, Paris

Baker JM, Ochsner TE, Venterea RT, Griffis TJ (2007) Tillage and soil carbon sequestration—what do we really know? Agric Ecosyst Environ 118:1–5

Bescansa P, Imaz MJ, Virto I, Enrique A, Hoogmoed WB (2006) Soil water retention capacity as affected by tillage systems under semiarid conditions in Navarra (NE Spain). Soil Tillage Res 87:19–27

Black AL, Tanaka DL (1997) A conservation tillage-cropping systems study in the Northern Great Plains of the United States. In: Paul EA, Elliott ET, Paustian K, Cole CV (eds) Soil organic matter in temperate agroecosystems. Long-term experiments in North America. CRC Press, Boca Raton, pp 335–342

Blanco-Canqui H, Lal R (2008) No-tillage and soil-profile carbon sequestration: an on-farm assessment. Soil Sci Soc Am J 72:693–701

Campbell CA, McConkey BG, Zentner RP, Selles F, Curtin D (1996) Long-term effects of tillage and crop rotations on soil organic C and total N in a clay soil in southwestern Saskatchewan. Can J Soil Sci 76:395–401

Carter MR (1994) Strategies to overcome impediments to adoption of conservation tillage. In: Carter MR (ed) Conservation tillage in temperate agroecosystems. CRC Press, Inc., Boca Raton, pp 3–19

Carter MR (2005) Long-term tillage effects on cool-season soybean in rotation with barley, soil properties and carbon and nitrogen storage for fine sandy loams in the humid climate of Atlantic Canada. Soil Tillage Res 81:109–120

Causarano HJ, Doraiswamy PC, McCarty GW, Hatfield JL, Milak S, Stern AJ (2008) EPIC modeling of soil organic carbon sequestration in croplands of Iowa. J Environ Qual 37:1345–1353

D'Haene K, Sleutel S, De Neve S, Gabriels D, Hofman G (2009) The effect of reduced tillage agriculture on carbon dynamics in silt loam soils. Nutr Cycl Agroecosyst 84:249–265

Deen W, Kataki PK (2003) Carbon sequestration in a long-term conventional versus conservation tillage experiment. Soil Tillage Res 74:143–150

DeFelice MS, Carter PR, Mitchell SB (2006) Influence of tillage on corn and soybean yield in the United States and Canada. Crop Manag. doi:10.1094/CM-2006-0626-01-RS

Du Z, Ren T, Hu C (2010) Tillage and residue removal effects on soil carbon and nitrogen storage in the North China Plain. Soil Sci Soc Am J 74:196–202

Ellert BH, Bettany JR (1995) Calculation of organic matter and nutrients stored in soils under contrasting management regimes. Can J Soil Sci 75:529–538

Follett RF, Castellanos JZ, Buenger ED (2005) Carbon dynamics and sequestration in an irrigated Vertisol in Central Mexico. Soil Tillage Res 83:148–158

Franzluebbers AJ (2005) Soil organic carbon sequestration and agricultural greenhouse gas emissions in the southeastern USA. Soil Tillage Res 83:120–147

Franzluebbers AJ, Steiner JL (2002) Climatic influences on soil organic carbon storage with no tillage. In: Kimble JM, Lal R, Follett RF (eds) Agricultural practices and policies for carbon sequestration in soil. Lewis Publishers, Boca Raton, pp 71–86

Giller KE, Witter E, Corbeels M, Tittonell P (2009) Conservation agriculture and smallholder farming in Africa: the heretics' view. Field Crops Res 114:23–34

Gregorich EG, Rochette P, VandenBygaart AJ, Angers DA (2005) Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. Soil Tillage Res 83:53–72

Halvorson AD, Wienhold BJ, Black AL (2002) Tillage, nitrogen, and cropping system effects on soil carbon sequestration. Soil Sci Soc Am J 66:906–912

Hernanz JL, Lopez R, Navarrete L, Sanchez-Giron V (2002) Long-term effects of tillage systems and rotations on soil structural stability and organic carbon stratification in semiarid central Spain. Soil Tillage Res 66:129–141

Johnson JMF, Reicosky DC, Allmaras RR, Sauer TJ, Venterea RT, Dell CJ (2005) Greenhouse gas contributions and mitigation potential of agriculture in the central USA. Soil Tillage Res 83:73–94

Kern JS, Johnson MG (1993) Conservation tillage impacts on national soil and atmospheric carbon levels. Soil Sci Soc Am J 57:200–210

Lal R (2004) Soil carbon sequestration to mitigate climate change. Geoderma 123:1–22

Liebig MA, Tanaka DL, Wienhold BJ (2004) Tillage and cropping effects on soil quality indicators in the northern Great Plains. Soil Tillage Res 78:131–141

Liebig MA, Morgan JA, Reeder JB (2005) Greenhouse gas contributions and mitigation potential of agricultural practices in Northwestern USA and western Canada. Soil Tillage Res 83:25–52

McConkey BG, Liang BC, Campbell CA, Curtin D, Moulin A, Brandt SA, Lafond GP (2003) Crop rotation and tillage impact on carbon sequestration on Canadian prairie soils. Soil Tillage Res 74:81–90

Ogle SM, Breidt FJ, Paustian K (2005) Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions. Biogeochemistry 72:87–121

Olson KR, Ebelhar SA (2009) Impacts of conservation tillage systems on long-term crop yields. J Agron 8:14–20

Peterson GA, Halvorson AD, Havlin JL, Jones OR, Lyon DJ, Tanaka DL (1998) Reduced tillage and increasing cropping intensity in the Great Plains conserves soil C. Soil Tillage Res 47:207–218

Puget P, Lal R (2005) Soil organic carbon and nitrogen in a Mollisol in central Ohio as affected by tillage and land use. Soil Tillage Res 80:201–213

Riley H, Borresen T, Ekeberg E, Rydgberg T (1994) Trends in reduced tillage research and practice in Scandinavia. In: Carter MR (ed) Conservation tillage in temperate agroecosystems. CRC Press, Inc., Boca Raton, pp 23–45

Sa JCM, Cerri CC, Dick WA, Lal R, Venske Filho SP, Piccolo MC, Feigl BE (2001) Organic matter dynamics and carbon sequestration rates for a tillage chronosequence in a Brazilian Oxisol. Soil Sci Soc Am J 65:1486–1499

Sisti CPJ, dos Santos HP, Kohhann R, Alves BJR, Urquiaga S, Boddey RM (2004) Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. Soil Till Res 76:39–58.

Six J, Conant RT, Paul EA, Paustian K (2002) Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241:155–176

So HB, Grabski A, Desborough P (2009) The impact of 14 years of conventional and no-till cultivation on the physical properties and crop yields of a loam soil at Grafton NSW, Australia. Soil Tillage Res 104:180–184

VandenBygaart AJ, Gregorich EG, Angers DA (2003) Influence of agricultural management on soil organic carbon: a compendium and assessment of Canadian studies. Can J Soil Sci 83:363–380

Wander MM, Bidart MG, Aref S (1998) Tillage impacts on depth distribution of total and particulate organic matter in three Illinois soils. Soil Sci Soc Am J 62:1704–1711

Wang XB, Cai DX, Hoogmoed WB, Oenema O, Perdok UD (2006) Potential effect of conservation tillage on sustainable land use: a review of global long-term studies. Pedosphere 16:587–595

Wanniarachchi SD, Voroney RP, Vyn TJ, Beyaert RP, MacKenzie AF (1999) Tillage effects on the dynamics of total and corn-reside-derived soil organic matter in two southern Ontario soils. Can J Soil Sci 79:463–480

West TO, Post WM (2002) Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci Soc Am J 66:1930–1946

Wienhold BJ, Andrews SS, Karlen DL (2004) Soil quality: a review of the science and experiences in the USA. Environ Geochem Health 26:89–95

Zinn YL, Lal R, Resck DVS (2005) Changes in soil organic carbon stocks under agriculture in Brazil. Soil Tillage Res 84:28–40