Climate drives global soil carbon sequestration and crop yield changes under conservation agriculture

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Abstract

Conservation agriculture has been shown to have multiple benefits for soils, crop yield and the environment, and consequently, no-till, the central practice of conservation agriculture, has rapidly expanded. However, studies show that the potential for carbon (C) sequestration in no-till farming sometimes is not realized, let alone the ability to maintain or improve crop yield. Here we present a global analysis of no-till induced changes of soil C and crop yield based on 260 and 1,970 paired studies, respectively. We show that, relative to local conventional tillage, arid regions can benefit the most from conservation agriculture by achieving a win-win outcome of enhanced C sequestration and increased crop yield. However, more humid regions are more likely to increase SOC only, while some colder regions have yield losses with soil C loss as likely as soil C gains. In addition to site-specific characteristics and management, a careful assessment of the regional climate is needed to determine the potential benefits of adopting conservation agriculture.

Introduction

Soils hold the largest terrestrial organic carbon (C) stock, storing roughly three times as much C as is in the atmosphere (Sanderman et al., 2017). With the dual benefit of removing atmospheric CO_2 and improving soil quality, increasing net soil C storage represents a promising opportunity for climate mitigation and sustainable food production to achieve Sustainable Development Goals (Rogelj et al., 2018; Vermeulen et al., 2019; Smith et al., 2019). Increased soil C stock has been associated with increase in crop yields, especially in Africa, Asia and Latin America (Soussana et al., 2019), and might partially offset the already detectable negative impacts on yield growth due to climate change (Lobell et al., 2011).

Soil disturbance by tillage has been widely shown to be a primary cause of the historical loss of soil organic carbon (SOC) (Lal, 2004), with estimated global C loses of 0.3–1.0 Pg C per year (Chappell et al., 2016). Conservation agriculture includes no-till, permanent crop residue retention, cover crop and crop rotation to increase crop residues on the soil surface. Its adoption has positive effects on soil physical properties through reducing susceptibility of soil aggregates to disruption, improving soil ability to capture and retain water, and reducing daytime soil temperature in spring and summer (Blanco-Canqui & Ruis, 2018). Conservation farming has therefore been proposed as a potential option to enhance SOC concentration for its multiple benefits on soil fertility and yield enhancement (Adhikari & Hartemink, 2016). Previous meta-analyses have revealed that SOC changes due to conversion to no-till were affected by regional climate (e.g. Ogle et al., 2012; 2019), soil type (e.g. Abdalla et al., 2016; Ogle et al., 2019) and management (e.g. Luo et al., 2010a). Specifically, for C sequestration, conversion to no-till has been shown variously to result in positive, negative, or nil effects (Powlson et al., 2014), highlighting the diverse responses and the need to understand the underlying controls.

More is known about the potential effects of conservation agriculture on crop productivity, with Pittelkow et al. (2015a; b) showing that climate, duration of no-till, irrigation, residue retention and crop rotation affect the yield response to no-till practices relative to conventional tillage. Crop residue production is closely related to soil C change under no-till relative to conventional tillage (Ogle et al., 2012), especially in farming systems without external input of fertilizer and manure (Kirkby et al. 2013).

Despite uncertainties and the lack of consistent benefits across regions and components of the cropping system, adoption of no-till has rapidly expanded from an area of 45 Mha in 1999 to over 180 Mha in 2015, equivalent to 12.5% of arable land worldwide (Kassam et al., 2019). This trend is expected to continue in the coming decades, despite challenges to adoption in Asia and Africa (Fischer & Hobbs, 2019). However, the distribution of potential C sequestration in no-till systems and consequently its overall contribution to the global soil C pool continues to be debated (West and Post, 2002; Smith et al., 2008; Luo et al., 2010a; Powlson et al., 2014). Globally, the controls and regions where no-till practice leads to both increased soil C accumulation and crop yield, and where either one might have a loss or no change, are poorly known.

Here we use decision tree analysis and meta-analysis of 260, globally distributed paired plots with SOC data under conventional tillage versus conservation agriculture (no-till with residue retention and crop rotation) for 5 to 52 years. Yield effects are studied by adding paired plots with yield data to 1,917 from Pittelkow et al. (2015a). We identify the potential for both SOC sequestration and crop yield gain under no-till relative to conventional tillage and the drivers determining the different outcomes. We identify the regions and climatic zones in which the adoption of conservation agriculture leads to win-win outcomes for climate change (mitigation through increased SOC) and food security (food production through increased yield). We also show regions where there is risk of soil C and/or crop yield loss after switching to conservation farming.

Methods

Our approach consisted of three major steps. First, we estimated the difference of SOC stocks between conservation and conventional farming with paired data from the literature. Second, we identified how the climate, soil type and management practices impact on gain or loss of SOC when conventional tillage converted to conservation farming. Third, we used meta-analysis to determine changes in SOC and crop yield after adoption of conservation farming as a function of climates.

Data sources-SOC dataset. Data were extracted from published peer-reviewed scientific journals and chapter of books that reported the paired data of SOC of conventional tillage and no-till practices with residue retention and cover crop or crop rotation from field experiments in various regions over the world. The studies included in the analysis were those cited in ISI Web of Science database until February 2019 with the keywords 'soil organic carbon' or 'soil organic matter' and 'no-till', 'no tillage' or 'zero tillage' or 'direct seeding'. Compiled data sets met the following criteria: (i) experiments of no-till lasting more than 5 years, which were used to reduce the instabilities at the beginning of the experiment (Smith, 2004); (ii) the duration of conventional tillage and no-till were the same; (iii) measured thickness of soil layers was not less than 30 cm. (iv) reduced tillage and minimum tillage practices were excluded and only continuous no-till (i.e. complete absence of tillage) was selected. If studies did not indicate removal of harvested straw, we assumed crop residue retention under no-till (amount of residue not measured or reported) (Table S1), given that no-till practices adopted across the globe mainly also use mulching (Farooq & Siddique, 2015).

Finally, 260 paired data of 138 locations from 115 published papers were involved in this study (Table S1). Paired soil samples were taken at 138 sites of 21 countries over the world (Fig.1, Table S2). Study location (country, site, latitude and longitude), soil physical and chemical properties (texture, particle composition, pH), climatic condition (mean annual temperature (MAT) and mean annual precipitation (MAP)), land use and management (crop rotation, residue incorporation, fertilizer input, and duration of the experiment) and organic carbon of conventional tillage and no-till from soil profiles of each publication were involved in the dataset. When climate data were not provided in the study, the MAP and MAT data were taken from the US National Climatic Data Center (http://www.ncdc.noaa.gov/) or the WorldClimate database (http://www.worldclimate.com). If raw data were unavailable, but only graphs or figures, GetData Graph Digitizer software (ver. 2.24, Russian Federation) was used to extract the data.

Data sources-crop yield dataset. Crop yield data were from Table S1 (n=53) and observations with a minimum of 5 years in duration (n=1,917) from Pittelkow et al. (2015a), thus excluding over 3500 of the Pittelkow studies which were of shorter duration; unfortunately, this large meta-analysis did not report SOC. The experimental sites of SOC dataset and crop yield dataset have no overlap (in latitude and longitude). Among them, 868 reported no-till combined with both residue retention and crop rotation, 576 reported no-till combined either residue retention or crop rotation, 106 reported no-till without residue retention or crop rotation, and information of residue or rotation was missing for the remaining 420 observations.

Soil organic carbon stock of conventional tillage and no-till. The equivalent soil mass-basis SOC stock at depth of *d* cm were then obtained by summing two parts – reported SOC to a depth adjacent to *d* cm, and the difference of the SOC between *d* cm and the adjacent depth, which was calculated by using Eqns. 1-2, respectively (Poeplau et al. 2011).

$$SOC_i = C_i \times BD_i \times d_i \times 10^{-1} \qquad \text{(Eqn. 1)}$$

$$SOC_{NT} = SOC_{NT0} + \frac{[\sum_{i=1}^{n}(BD_{CT})_i \times (d_{CT})_i - \sum_{i=1}^{n}[(BD_{NT0})_i \times (d_{NT0})_i] \times (SOC_{NT0})_n}{(BD_{NT0})_n \times (d_{NT0})_n} \qquad \text{(Eqn. 2)}$$

where C is the soil organic carbon concentration (g kg^{-1}), SOC is soil organic carbon stock (Mg C ha^{-1}), BD is soil bulk density (g cm^{-3}), and d is soil depth (cm) (Palm et al., 2014). SOC_{NT} and SOC_{NT0} are the SOC stores of no-till with and without the equivalent soil mass correction to the i layer.

For the studies where soil bulk densities are not available (Table S3), it was estimated by using Eqn. 3. There are many equations available to estimate missing BD (e.g. Adams, 1973; Mann, 1986; Poeplau et al., 2011; Sequeira et al., 2014). Among these, the Adams equation (Adams, 1973) has been widely used because of its explanation of soil components. The parameters of a1 and a2 were 0.244 and 1.64 for organic and mineral parts in the original equation. In this study, we kept a1 as a constant of 0.244, and determined a2 by using data in Table S1. We converted SOC to SOM by dividing a coefficient of 0.58 (Mann, 1986) when the SOM is not given in the literature.

$$BD = \frac{100}{\frac{\%SOM}{a_1} + \frac{100 - \%SOM}{a_2}} \qquad \text{(Eqn. 3)}$$

Since soil bulk density was affected by tillage operations (Osunbitan et al., 2005), the a2 were determined for conventional tillage and no-till respectively. Fitting Eqn. 3 by using paired data of BD and SOM which were given in publications, the a2 were determined to be 1.547 and 1.591 for conventional tillage and no-till, respectively (Table S4).

SOC stock in the mineral soil up to a depth of 30 cm under conventional tillage and no-till respectively were calculated. When there was a certain depth to 30 cm in the literature, we simply summed the SOC of each layer to 30 cm. Otherwise, the following two depth functions (Eqn. 4a, b) were used to fit the vertical distribution of SOC stocks for each soil profile (Jobbágy and Jackson, 2002).

$$\log Y = a_1 \times \log d + a_0 \qquad \text{(Eqn. 4a)}$$

$$Y = b_1 \times \log d + b_0 \qquad \text{(Eqn. 4b)}$$

where Y represents the cumulative SOC stock (Mg C ha^{-1}) within a 0-d cm range of soil depth. We determined the coefficients a0, a1, b0, b1 at a given soil profile, and calculated the cumulative SOC stock using Eqns. 4a-b. The best fit function was determined via calculation of the minimum mean predictive error. The gain or loss of SOC stocks (Mg C ha^{-1}) and the SOC change rate (Mg C ha^{-1} yr^{-1}) with adoption of relative to conventional tillage were used to evaluate the no-till effect. Each observation of SOC change was calculated with Eqn. 5.

$$\Delta SOC = SOC_{NT} - SOC_{CT} \quad \text{(Eqn. 5)}$$

$$\Delta SOC_R = \frac{\Delta SOC}{N} \quad \text{(Eqn. 6)}$$

where Δ_{SOC_R} refers to annual gain or loss of SOC stock under no-till practice relative to conventional tillage, and N is duration years after no-till.

Decision tree analysis. The aims of the current study centered on investigating some of the variables that predicted the ΔSOC and ΔYield with the help of decision tree techniques and comparing the differences in ΔSOC and ΔYield prediction as a categorical and continuous variable by utilizing the classification and regression tree (CRT). The CRT (Breiman et al., 1984), a nonparametric modeling approach, was employed to relate the ΔSOC and ΔYield to climatic conditions, soil characteristics and agricultural management (Zheng et al., 2009), and to identify the most major variables controlling positive or negative sign of ΔSOC and ΔYield.

The variables involved in CRT analysis including annual mean temperature (MAT, °C) and precipitation (MAP, mm), humidity index (HI, mm°C^{-1}), which was calculated as the ratio between annual mean precipitation and mean temperature (MAP/MAT) (e.g. Alvarez & Lavado, 1998; Quan et al., 2013; Ponge et al., 2014), clay content (%), clay plus silt content (%), soil pH, experimental duration of no-till (yr), difference of annual carbon input between no-till and conventional tillage (ΔC_{input}, MgC ha^{-1} yr^{-1}) and annual fertilizer nitrogen input (N_{input}, kg N ha^{-1} yr^{-1}), numbers of crops during experiment period, annual crops, rotation with or without legumes. Description and frequency distribution of parameters in this study were shown in Table S5 and Fig. S1. The first nine variables were defined as numeric variables, the consequent two were ratings, and the last one was categorical type. The CRT technique was performed using SPSS 21.0 (SPSS Inc., Chicago, IL, USA). Statistical significance was assessed at $p \le 0.05$. Impurity measure of Gini was selected. The maximum tree depth was using default level of 5. Minimum cases in parent and child nodes were 100 and 50 respectively due to limited sample size. The CRT default setting was used to deal with missing values. The optimum tree was selected using 10-fold cross validation. The CRT analyses were performed using the subset of samples with the ΔSOC available. The dependent variable was ΔSOC, which was categorical (i.e. ΔSOC≤0, ΔSOC>0). When the ΔSOC≤0 (score 1), it means that no-till practice does not increase SOC when compared to conventional tillage. The ΔSOC>0 (score 2) therefore means soil carbon gain following no-till adoption.

Meta-analysis

We chose the log response ratio (RA) as the effect size for SOC and Yield comparisons. RA is calculated as the ratio of its value in the experimental treatment (Xe) to that in the control treatment (Xc). In our study, Xe is the value of the measured variable in no-till cropland, and Xc is the value of the variable in tilled cropland. To improve statistical performance, RA was log-transforming such that ln (RA) = ln (Xe) – ln (Xc). In meta-analysis, individual observations are usually weighted by the inverse of their variance, but not all of the selected studies provided the sampling variance (e.g., standard deviation). Sample size, however, was available in all the references. Thus, to include as many studies as possible, studies were weighted by sample size (Adams, 1997)

$$w=n_c n_t/(n_c+n_t) \quad \text{(Eqn.7)}$$

where w refers to the specific weight of a given pair of data, and nc and nt are sample sizes for the control and no-till, respectively. Given that studies differed in sample sizes, more weights are given to large sample sizes. Finally, there are 256 cases of ΔSOC (the number of replicates of the other 4 cases are missing) and 1550 cases of Δ yield (residue management of the other 420 cases are missing) involved in meta-analysis.

Resampling methods (e.g., bootstrapping) were used to calculate bias-corrected 95% confidence intervals (CIs) around the mean effect size. If the 95% CI of the effect size for a variable did not overlap with zero, the effect of restoration on the variable was considered significant. The percentage change of the SOC was obtained by the following equation: ($e^{RA_{++}}$− 1) × 100%, where RA_{++} is the mean response ratio.

To determine whether there were significant differences in mean response ratio among various categories, we employed randomization tests to calculate the significance level for between-class heterogeneity (Q_B, Adams, 1997). The meta-analysis was conducted using the statistical software Meta-Win (Rosenberg et al., 2000).

Results

Soil C sequestration under conservation farming. Based on data from 260 paired plots from 115 published papers (Table S1), the rate of SOC sequestration of no-till plots, relative to conventional tillage (ΔSOC), ranged from -2.75 to 3.99 MgC ha^{-1} yr^{-1}, averaged 0.35±0.05 (SE) MgC ha^{-1} yr^{-1}, measured by the mass-basis method to a depth of 30 cm (Fig S1). Of all pair-plots, 76 (29%) showed zero or negative ΔSOC, and the remaining 184 cases (71%) had positive ΔSOC. We conducted decision tree analysis by trying each possible combination of environmental and anthropogenic factors as the tree classifier, which comprising MAT, MAP, HI, soil clay content (%), clay plus silt content (%), soil pH, experimental duration of no-till (yr), difference of annual mean C input between no-till and conventional tillage (ΔC_{input}, MgC ha^{-1} yr^{-1}), annual fertilizer nitrogen input (N_{input}, kg N ha^{-1} yr^{-1}), crop diversity in rotation, annual crops, and rotation with or without legumes (Table S5).

The HI was the most important and the only statistically significant ($p<0.05$) factor in separating the positive or negative ΔSOC (Fig. 1a). Under less humidity (HI≤89), conversion to no-till is likely (79% of the pair-plots) to increase SOC with a mean of 0.40±0.05 (±SE) MgC ha^{-1} yr^{-1} (Fig.S2). Regions with HI≤89 include mid and eastern parts of North America and California, Western parts of South America, sub-Sahara Africa, southeastern Australia, central and southern parts of Europe, India, and eastern and southern of China (Fig. 2). In contrast, no-till conducted in croplands with an HI>89 are as likely as not to increase SOC sequestration, with 55% probability of negative ΔSOC compared to 45% to gain C, with a mean of 0.19±0.14 MgC ha^{-1} yr^{-1} (Fig. S2). Croplands of most regions in Canada, northern Europe, Southeast Asia and the northeast of China, which have an HI>89, have risk C loss when no-till replaces conventional tillage (Fig. 2). Although soil characteristics, different C inputs, and duration of no-till are known to effect to varying degree SOC turnover, no further branch was statistically significantly to make the decision tree go deeper (Fig. 1b).

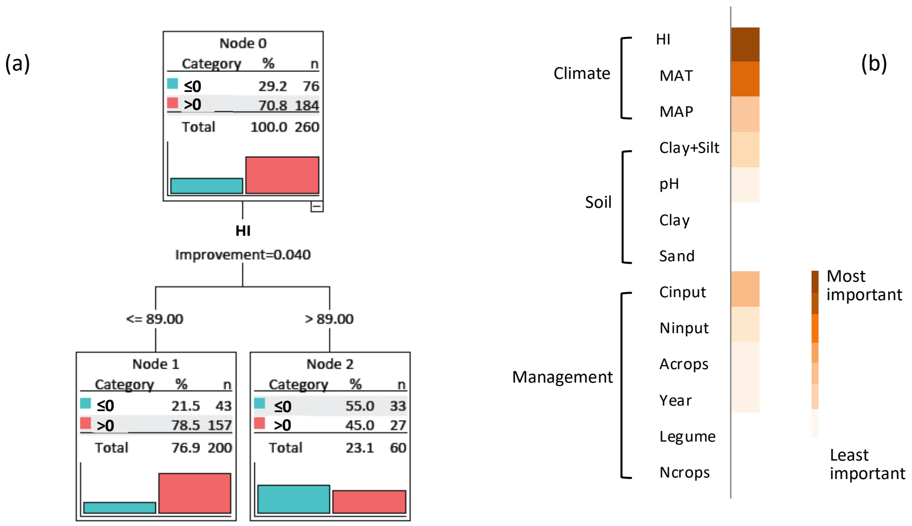

Figure 1. Decision tree predicting gain or loss of SOC resulting from conventional to conservation farming based on environmental variables and agronomic practices. (a) Tree prediction. Blue is SOC stocks under no-till system that are

lower than or equal to that under conventional tillage. Red is SOC under no-till system that is higher than that under conventional tillage. (b) Importance of climate, soil characteristics and agronomic practices used in the tree analysis. Cinput is the difference of C input (MgC ha^{-1} yr^{-1}) between conservation and conventional framing. Ninput is the input of nitrogen fertilizer (kgN ha^{-1} yr^{-1}). Acrops is the number of annual harvested crops (or multiple-cropping index). Year is the duration of which the conservation practice has been implemented. Legume is whether legumes (N-fixers) were involved in the rotation. Ncrops is the crop diversity in the crop rotation.

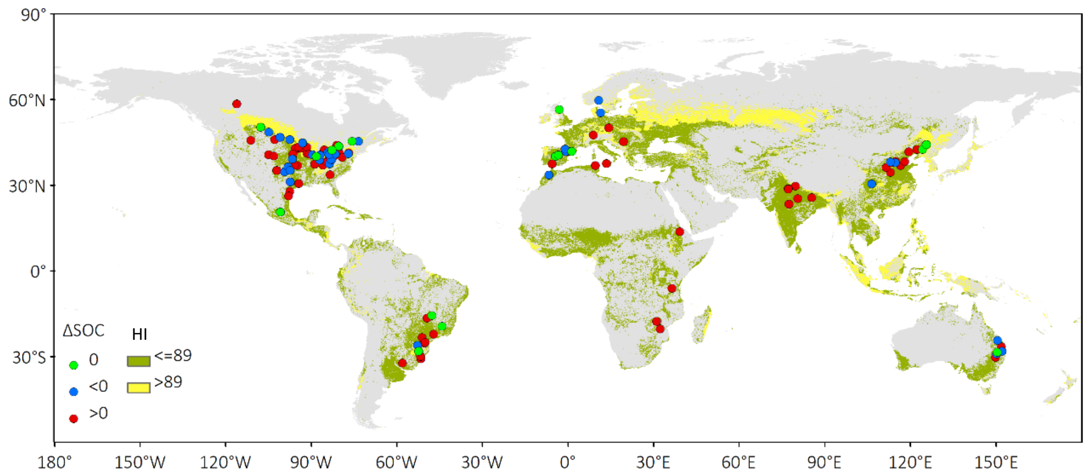

Figure 2. Locations of the SOC pair plots included in this study (n= 138 locations). The green and yellow colors represent the HI, which is calculated using the ratio of mean precipitation to mean temperature for 1970-2000 (http://www.worldclim.org/). The blue and red dots refer to the statistically significant loss and gain of SOC stocks (MgC ha^{-1}), respectively, between conservation and conventional practice. Light green dots refer to no change of SOC according to the literature, which indicates that no statistically significant difference in SOC stock was detected in the 0-30 cm layer. For the sites which have more than one plot (Table S1), the median value of ΔSOC is used.

Soil C sequestration under conservation farming in deeper soil layers. Previous studies argued that under no-tillage, soil C sequestration might occur in the upper soil layers but might decline in deeper layers, such that the total soil C content remains unchanged (Luo et al., 2010a; Powlson et al., 2014; Ogle et al., 2019). Based on 62 pair-plots (49 sites) with global coverage and sampled down to 60 cm deep (Table S1), we found that the difference of SOC sequestration between conservation and conventional tillage decreased with soil depth and that the relationship is described well by a negative power function (Fig. 3a). Thus, despite the smaller benefits of no till at depth, SOC in the overall soil profile down to 60 cm increased with conservation relative to conventional tillage. A smaller dataset with SOC estimates down to 100 cm suggests that the overall SOC increased is also maintained to that depth (Fig. 3a).

Among the total of 62 pair-plots to a 60 cm depth (Table S1), 46 cases (74%) gained C and 16 cases (26%) lost C at 0-30 cm depth, while 26 cases (42%) gained C and 36 cases (58%) lost C at 30-60 cm depth. The average SOC sequestration rate (ΔSOC_R, annual SOC change under conservation relative to conventional tillage) is 0.92±0.14 Mg ha^{-1} yr^{-1} for the 0-30 cm layer and 0.02±0.06 Mg ha^{-1} yr^{-1} for 30-60 cm layer for the 46 cases with C gains. Carbon was lost at a rate of -0.73±0.18 and -0.85±0.26 Mg ha^{-1} yr^{-1} for the 0-30 cm layer and 30-60 cm layer, respectively, for the 16 cases with C loss at 0-30 cm. Comparing to changes in SOC in the 0-30 cm, C gain or loss in deeper layers contributes little to the C stock of the whole soil profile, especially for the C gain cases. Overall, the average SOC sequestration rates are 0.35±0.05 Mg ha^{-1} yr^{-1} (n=260) and 0.24±0.21 Mg ha^{-1} yr^{-1} (n= 62) for the 0-30 cm layer and 0-60 cm layer, respectively, but the difference is not statistically significant. Our analysis reveals a significant positive linear relationship of ΔSOC_R between 0-30 cm and 30-60 cm for the 16 cases with C loss (Fig. 3b), suggesting a synchronous decrease in topsoil and deeper layers. Of the 46 cases in which the 0-30 cm layer gained SOC, about half (n=22) also gained SOC at 30-60 cm depth when adopting conservation practice (Fig. 3b). These results suggest highly site-specific effects on the effects of conservation farming at depth (Fig. 3b).

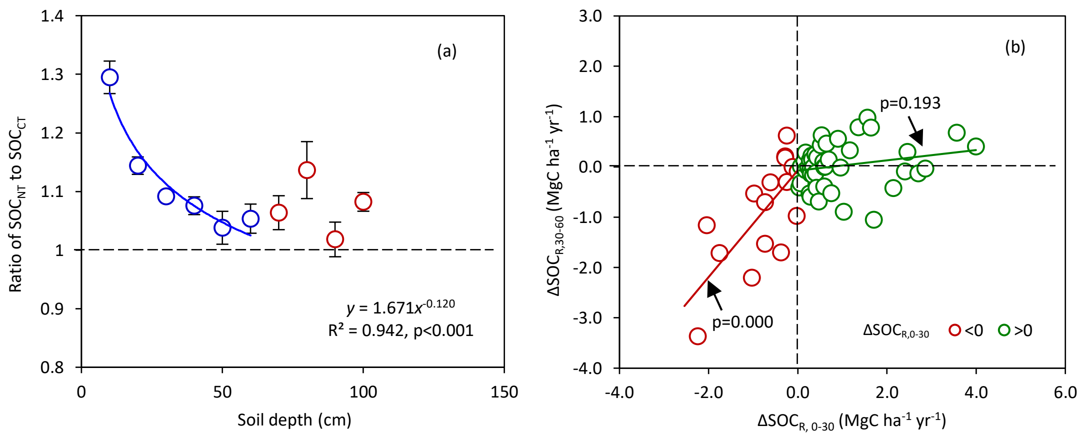

Figure 3. SOC under conservation relative to conventional tillage to a soil depth of 100 cm. (a) Ratio of SOC_{NT} (SOC stocks under conventional farming) to SOC_{CT} (SOC stocks under conventional tillage) and sampled soil depth grouped by depth layer. Blue and red circles are the ratios at ≤60 cm and >60 cm depth, respectively. The solid blue line is a fit to 60 cm depth; SOC deeper than 60 cm (60-100 cm) is not used to fit the model due to small dataset (Table S1). Ratio of 1 (dash line) indicates no SOC gain or loss under conservation compared to conventional tillage. Values above the dashed line indicate SOC gains when cropland converted from conventional tillage to conservation practice. Data are means ± SE. (b) Relationship between annual SOC change (ΔSOC_R) 0-30 cm and 0-60 cm depths under conservation relative to conventional tillage. The red and green circles indicate SOC loss and gain under conservation practice at 0-30 cm depth relative to conventional tillage respectively. All sites with measurement to 30 and 60cm (n=62, Table S1). The p-value is statistical significance of fitting line.

SOC stock and crop yield under conservation farming. To understand the global patterns of the effect of conservation agriculture on both SOC sequestration and crop yield, we use the SOC data described above and crop yield data from experiments with a minimum of 5 years in duration (n=1,917) from Pittelkow et al. (2015a) and additional crop yield data from our dataset (n=53, Table S1); across the 1,970 pair of data with the effect of no-till on mean crop yield was -0.18±0.03 Mg ha^{-1}. As we found for the impacts on SOC stocks, HI was also the statistically significant factor in our global tree analysis influencing changes in crop yield under no-till (Fig. S3). Crop yield gain occurred in 51% pair plots after adopting no-till in dry to humid climates (HI≤78 in Fig. S3), while it declined in 64% of the pair plots in humid climates (HI>78). The influence of other managements following no-till farming is not significant at global scale indicating an overriding effect of climate and/or a more regionally specific role of management that does not show in a global analysis (Fig. S3).

We took the 256 results on SOC from our meta-analysis and the above combined yield results and classified them according to HI intervals (<40, 40-60, 60-80, 80-100, >100) (Table S6). We found that no-till in regions with HI<40, both SOC sequestration and crop yield increase when synchronous crop residue retention and crop rotation are applied using all components of conservation agriculture (Fig.

4a). Crop yield does not improve under no-till practice alone. Most croplands in India, north-central Africa and Australia are in this region (Fig. 5). The potential for SOC sequestration declines with increasing wetter/cooler conditions for regions between 40≤HI<100 (Fig. 4a-b). Crop yield remains unchanged only when residue retention and crop rotation are applied together (Fig. 4a). In regions with HI>100, where most croplands in Canada, north Europe, north China, Japan and the Philippines are located (Fig. 5), conservation agriculture is about as likely as not to gain SOC (14 out of 35 cases gain C) with negative crop yield regardless of whether crop residue and rotation are also applied (Fig. 4a). We found a consistent decline of annual change in SOC stocks (ΔSOC_R) and crop yield ($\Delta Yield_R$) with increasing HI (Fig. 4b) and a positive relationship between them (Fig. 4c). The resulting increased SOC stocks might be expected to offset partially or totally the decline in crop yield after no-till adoption. Higher crop yields can be achieved when SOC sequestration rate is higher than 0.4 MgC ha^{-1} yr^{-1} (Fig. 4c).

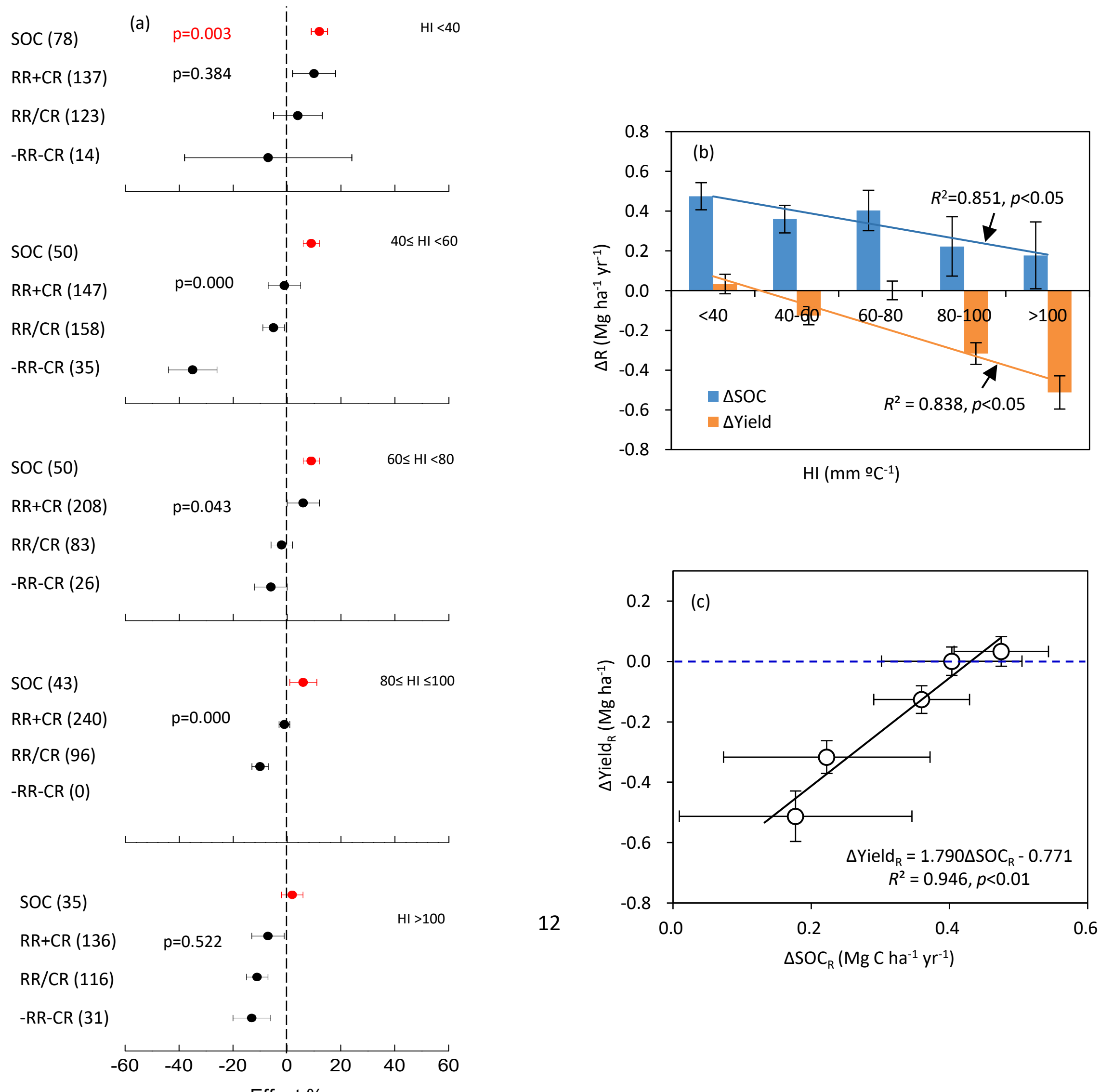

Figure 4. Comparison of effect on SOC and crop yield in no-till relative to conventional farming systems under different climate classes. (a) refers to HI (annual mean precipitation to annual mean temperature ratio, MAP/MAT) of <40, 40-60; 60-80; 80-100 and >100, respectively. Red dots refer to SOC stocks in 0-30cm depth. Black dots are crop yields. RR+CR is crop residue retention + crop rotation; RR/CR is either residue or rotation"; -R-R is without residue and without rotation. The numbers of observations are shown in parenthesis. Horizontal bars show the 95% confidence interval. Significant differences between categories are indicated by *p* values based on randomization tests. (b) response of SOC and crop yield after adoption of no-till with residue retention or crop rotation (cover crop) as a function of climate. (c) relationship between ΔSOC_R and $\Delta Yield_R$. Dashed line refers the crop yield under no-till equals to that under conventional tillage, indicating crop yield remains unchanged. Data source of (b) and (c) is in Table S6.

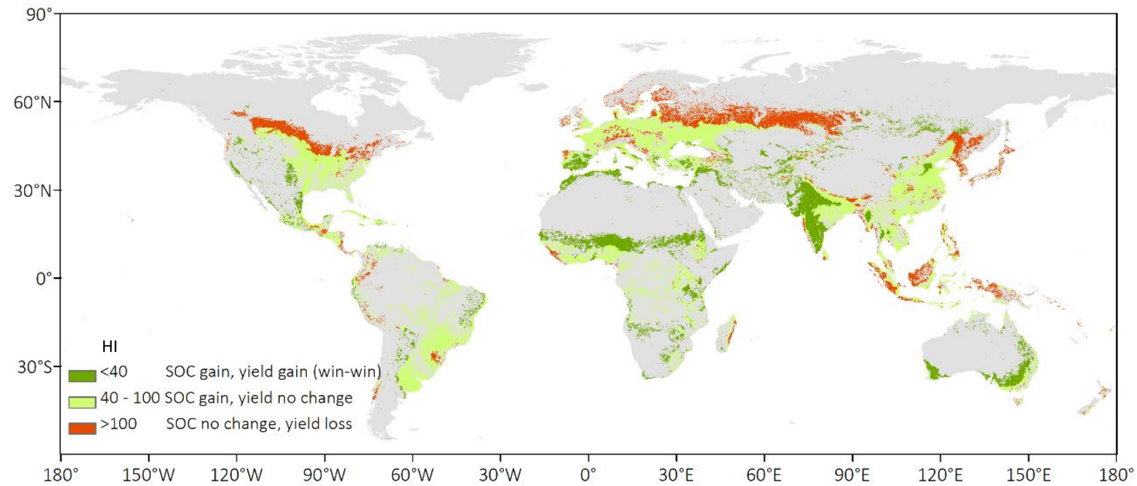

Figure 5. Global patterns of changes in soil organic carbon and crop yield after adopting conservation agriculture.

Discussion

Conservation agriculture can play a critical role in the development of sustainable agricultural systems in light of growing food demand and environmental change (Kassam & Brammer, 2012). Our study shows that croplands in arid and warmer regions with the HI<40 have potential for adopting conservation agriculture as a win-win solution to climate change mitigation and meeting food security challenges (Fig. 4a, Fig.5). Soil organic C in tillage soils of warmer regions with HI<40 are generally favorable for decomposition provided water is not limiting (e.g. irrigation). Also, the major benefit of conservation agriculture in dry area cropping is extra soil moisture conservation in the fallow period preceding crop planting provided weeds are controlled (Fischer & Hobbs, 2019). In such cases, conservation farming reduces soil temperature and improves rainfall infiltration, and reduces soil evaporation by zero disturbance and providing soil cover through mulch residue which has potential to suppress the release of C from soil (Kahlon et al., 2013). Improved crop yield induced by conservation farming also has important repercussions for SOC accumulation by increasing residue returns to the soil which may contribute to increases in soil organic matter.

In semi-arid to humid regions with 40≤HI<100, conservation agriculture has the potential to increase SOC while crop yield largely remains unchanged, thereby providing a benefit only for climate change mitigation (Fig. 4a, Fig. 5). In these regions no-till, when not complemented with residue return and/ or crop rotation risks decreasing crop yield. Beyond the benefits on SOC and yield, conservation farming has additional positive environmental outcomes, such as preventing wind and water erosion (Fischer & Hobbs, 2019). Therefore, no-till practice could be adopted for short periods of time (multiple years; Powlson et al., 2014). Overall, we found that conservation agriculture positively impacts SOC accumulation and prevents crop yield reduction in regions of HI<100. Most croplands in China, India and Sub-Sahara Africa, where traditional tillage is widely practiced, are likely to benefit from conservation farming, including for climate mitigation. In regions with HI>100 (cold humid and tropical humid climates, consistent with Porwollik et al., 2019) (Fig. 4a, Fig. 5), the shift to no-till, even with residue retention and crop rotation, is likely to result in negative outcomes. In cool, moist environments, decreased soil temperature and waterlogging from mulch cover may have a disadvantage for early crop seed germination and crop growth, which is associated with lower crop yield (Pittelkow et al., 2015a; Blanco-Canqui & Ruis, 2018). In tropical humid environments, waterlogging due to crop residue retention, especially after heavy rains, also leads to reduced crop yield (Thierfelder et al., 2014; Powlson et al., 2014). Our analysis identified significant effect of HI but explained only part of the variation of ΔSOC and ΔYield, and other important factors exist. Part of the variation could be explained by duration, fertilizer, soil texture etc. (e.g. Luo et al., 2010a; Kirkby et al., 2013; Pittelkow et al., 2015a), but could not be detected with our methodology (Fig. 1) or were not reported. Variations due to irrigation of some sites, a key site variable rarely was reported in the dataset, especially the SOC dataset used here (Table S1).

Our results suggested that crop yields have risk of decrease under no-till in many regions over the world (Fig. 4 a-b, Fig. 5) but can be achieved when SOC sequestration rate is higher than 0.4 MgC ha^{-1} yr^{-1} (Fig. 4c), accounting for at least 2 MgC ha^{-1} yr^{-1} of extra residue C into no-till soils. Globally, application of fertilizer at rates of up to 85 kg N ha^{-1} yr^{-1} may prevent yield declines (Lundy et al., 2015) and the supply of nutrients can improve soil organic matter formation (Kirkby et al. 2013) in no-till croplands, although the use of fertilizer and its associated N_2O emission will easily offset the soil C gains (Shcherbak et al., 2014). Therefore, integrated sustainability assessments of conservation farming are needed.

Previous studies suggest that crop C input in tillage and no-till farming follows the same pattern as crop yield: C input decrease by more than 15% consistent with a similar decline in SOC cause by tillage (Ogle et al., 2012). However, conventional tillage with ploughing improves soil moisture conditions, which combined with crop residue incorporation, can lead to a long-term maintenance of SOC stock and crop yield. The implications of our findings for targeting areas which benefit from conservation farming remain uncertain for some regions, especially for South Asia, where few long-term and deep soil paired SOC data of no-till and conventional tillage were found. Despite current uncertainties, our results can guide the adoption, or otherwise, of conservation agriculture in many parts of the world, particularly in arid regions and growing areas of the world experiencing drying trends due to current and future climate change (Cook et al., 2014).

Our analysis also provides insights into previous debates about whether no-till can increase C stock of the top soil layers (less than 30 cm), which could be offset by C loss in deeper layers (e.g. Angers et al., 2008; Luo et al., 2010a; Powlson et al., 2014). We found that for the cases when SOC under no-till relative to conventional tillage increases in the top 30 cm, it was likely that the 30-60 cm layer also increased SOC, albeit only by small fraction compared to the top layer. Thus, it is likely that under no till, SOC increases throughout the soil profile to deeper soil layers (Fig. 3a), albeit with large uncertainties due to sparse or absent data in many regions (Fig. 2; Table S1). Data limitations also prevents assessment of factors that are known to be important such as plow depth and frequency, which influence the quality and quantity of residues incorporated to different depths (Franzluebbers, 2002). The available tillage depth in our dataset varied from 10 cm to 50 cm, while the SOC stratification study was inconsistent with tillage depth. Deep C accumulation in no-till systems, with higher bulk density (Table S4) due to more soil compaction compared to conventional tillage, can be further enhanced by planting crops with deep and extensive rooting systems (Dou et al., 2007; Soane et al., 2012).

In regions where SOC increased under conservation agriculture, a key issue is to understand how long the gains can continue before SOC reaches a saturation point after which no more C can be sequestered, for a given soil and climate envelope (West & Six, 2007). We find no statistically significant relationship between the ΔSOC_R and the duration of no-till system, which in our dataset ranges from 5 to 52 years (Table S1). This result suggests that soil C saturation is reached in various systems during the studies, which prevents saturation year and annual sequestration rates from being identified. Few observations have reported the temporal variation in SOC under conventional tillage, with an example of a 17-year field study in Spain that the maximum C sequestration of 8.43 MgC ha^{-1} after 8 years of having adopted no-till practice with a subsequent decline (Lòpez-Fando & Pardo, 2011). These results highlight the possibility of no additional C gains in regions where no-till has been practiced for many years such as in regions of the US, Brazil and Australia (Fischer & Hobbs, 2019). While a few long-term studies within a particular climatic region are simply not enough to describe all of the peculiar management variations that can exist among farmers within a region. Multiple studies are needed throughout the globe to be able to adequately characterize the interactions of multiple management factors on SOC sequestration and yield changes with adoption of conservation agriculture. A focused effort to study the time dynamics of C accumulation under conservation agriculture will improve our understanding of the C sequestration potential and potential for sink saturation.

Conclusions

Our study shows that global patterns of soil carbon sequestration and crop yield change due to the adoption of conservation agriculture are largely driven by climate conditions. The highly diverse outcomes at the regional level, with positive, negative or no effects on soil carbon and crop yield helps explain past uncertainties and disagreement on the potential benefits of adopting conservation agricultural practices. The regional patterns also highlight the likely importance of many site-specific soil and management variables in determining the final outcomes of no-till. In the regions where SOC increases under no-till, particularly in dry regions, the C benefits are preserved throughout the entire soil profile suggesting net C sequestration, and therefore a net climate change mitigation effect. It is possible to adopt no-till practices and have gains in both soil carbon and crop yield, but the contrary is also possible, particularly in cold regions. Our study underscores the importance of assessing the climate conditions, and site-specific practices, to understand the potential benefits of adopting no-till and other practices of conservation agriculture.

Acknowledgements

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Author	Year	Country	Site	Latitude	Longitude	MAT	MAP
Lòpez-Fando & Pardo	2011	Spain	CCMA-CSIC, Santa Olalla, Toled	40.05	-4.43	14.0	431
Lòpez-Fando & Pardo	2011	Spain	CCMA-CSIC, Santa Olalla, Toled	40.05	-4.43	14.0	431
Lòpez-Fando & Pardo	2011	Spain	CCMA-CSIC, Santa Olalla, Toled	40.05	-4.43	14.0	431
Lòpez-Fando & Pardo	2011	Spain	CCMA-CSIC, Santa Olalla, Toled	40.05	-4.43	14.0	431
Lòpez-Fando & Pardo	2011	Spain	CCMA-CSIC, Santa Olalla, Toled	40.05	-4.43	14.0	431
Lòpez-Fando & Pardo	2011	Spain	CCMA-CSIC, Santa Olalla, Toled	40.05	-4.43	14.0	431
Lòpez-Fando & Pardo	2011	Spain	CCMA-CSIC, Santa Olalla, Toled	40.05	-4.43	14.0	431
Lòpez-Fando & Pardo	2011	Spain	CCMA-CSIC, Santa Olalla, Toled	40.05	-4.43	14.0	431
Lòpez-Fando & Pardo	2011	Spain	CCMA-CSIC, Santa Olalla, Toled	40.05	-4.43	14.0	431
Lòpez-Fando & Pardo	2011	Spain	CCMA-CSIC, Santa Olalla, Toled	40.05	-4.43	14.0	431
Lòpez-Fando & Pardo	2011	Spain	CCMA-CSIC, Santa Olalla, Toled	40.05	-4.43	14.0	431
Lòpez-Fando & Pardo	2011	Spain	CCMA-CSIC, Santa Olalla, Toled	40.05	-4.43	14.0	431
Hernanz et al.	2009	Spain	Alcalá de Henares, Madrid	40.48	-3.37	13.1	430
Hernanz et al.	2009	Spain	Alcalá de Henares, Madrid	40.48	-3.37	13.1	430
Hernanz et al.	2009	Spain	Alcalá de Henares, Madrid	40.48	-3.37	13.1	430
Hernanz et al.	2009	Spain	Alcalá de Henares, Madrid	40.48	-3.37	13.1	430
Hernanz et al.	2009	Spain	Alcalá de Henares, Madrid	40.48	-3.37	13.1	430
Hernanz et al.	2009	Spain	Alcalá de Henares, Madrid	40.48	-3.37	13.1	430
Hernanz et al.	2009	Spain	Alcalá de Henares, Madrid	40.48	-3.37	13.1	430
Hernanz et al.	2009	Spain	Alcalá de Henares, Madrid	40.48	-3.37	13.1	430
Hernanz et al.	2002	Spain	Alcalá de Henares, Madrid	40.48	-3.37	13.1	430
Hernanz et al.	2002	Spain	Alcalá de Henares, Madrid	40.48	-3.37	13.1	430
Álvaro-Fuentes et al.	2008	Spain	Selvanera	41.83	1.28	13.9	475
Álvaro-Fuentes et al.	2008	Spain	Agramunt	41.80	1.12	14.2	430
Álvaro-Fuentes et al.	2008	Spain	Peñaflor	41.73	-0.77	14.5	390
Álvaro-Fuentes et al.	2008	Spain	Peñaflor	41.73	-0.77	14.5	390
Fernández et al.	2007	Spain	Seville	37.40	-5.58	16.7	515
Fernández et al.	2007	Spain	Seville	37.40	-5.58	16.7	515
Hermle et al.	2008	Switzerlanc	Tanikon	47.48	8.90	8.4	1183
Manojlovic´ et al.	2008	Russia	Novi Sad	45.19	19.50	11.1	608
Manojlovic´ et al.	2008	Russia	Novi Sad	45.19	19.50	11.1	608
Yang & Kay	2001	Canada	Southern Ontario	44.00	-81.00	6.7	943
Yang & Kay	2001	Canada	Southern Ontario	44.00	-81.00	6.7	943
Yang & Kay	2001	Canada	Southern Ontario	44.00	-81.00	6.7	943
Poirier et al.	2008	Canada	Quebec	45.30	-73.35	6.3	1100
Soon et al.	2007	Canada	Alberta	58.38	-116.03	-0.9	380
Soon et al.	2007	Canada	Alberta	58.38	-116.03	-0.9	380
Gregorich et al.	2006	Canada	Ottawa, Ontario	45.37	-75.72	5.8	880
Shi et al.	2001	Canada	Woodslee, Ontario	42.22	-82.73	8.7	827
Deen & Kataki	2003	Canada	Ontario (University of Guelph)	43.50	-80.25	5.5	863
Ramnarine	2010	Canada	Ontario (Elora Research Statior	43.63	-80.42	6.4	900
Potter et al.	1998	U.S.	Bushland, Texas	35.18	-102.08	14.0	473
Potter et al.	1998	U.S.	Bushland, Texas	35.18	-102.08	14.0	473
Potter et al.	1998	U.S.	Bushland, Texas	35.18	-102.08	14.0	473
Potter et al.	1998	U.S.	Bushland, Texas	35.18	-102.08	14.0	473
Potter et al.	1998	U.S.	Temple, Texas	31.08	-97.33	19.0	860
Potter et al.	1998	U.S.	Temple, Texas	31.08	-97.33	19.0	860
Potter et al.	1998	U.S.	Temple, Texas	31.08	-97.33	19.0	860
Potter et al.	1998	U.S.	Temple, Texas	31.08	-97.33	19.0	860
Potter et al.	1998	U.S.	Corpus Christi, TX	27.77	-97.50	22.0	660
Zibilske et al.	2002	U.S.	Weslaco, Texas	26.15	-97.95	23.1	603
Dou et al.	2007; 2008	U.S.	Burleson county, Texas	30.53	-94.43	20.0	980
Dou et al.	2007; 2008	U.S.	Burleson county, Texas	30.53	-94.43	20.0	980
Dou et al.	2007; 2008	U.S.	Burleson county, Texas	30.53	-94.43	20.0	980
Yang & Wander	1999	U.S.	University of Illinois, Urbana, IL	40.10	-88.20	18.6	657
Olson et al.	2005	U.S.	southern Illinois	37.37	-88.75	21.3	750
Olson et al.	2005	U.S.	southern Illinois	37.37	-88.75	21.3	750
Olson et al.	2005	U.S.	southern Illinois	37.37	-88.75	21.3	750
Syswerda et al.	2011	U.S.	Michigan	42.40	-85.40	9.0	920
Hernandez-Ramirez et al.	2011	U.S.	Sac, Lowa	42.43	-95.15	8.0	838
Venterea et al.	2006	U.S.	Minnesota	44.75	-93.07	6.4	879
Venterea et al.	2006	U.S.	Minnesota	44.75	-93.07	6.4	879

Gal et al.	2007	U.S.	Indiana	40.47	-87.00	12.0	950
Venterea & Stanenas	2008	U.S.	Rosemount, MN	44.75	-93.07	6.4	879
Dolan et al.	2006	U.S.	Rosemount, MN	44.75	-93.07	7.0	820
Dolan et al.	2006	U.S.	Rosemount, MN	44.75	-93.07	7.0	820
Dolan et al.	2006	U.S.	Rosemount, MN	44.75	-93.07	7.0	820
Dolan et al.	2006	U.S.	Rosemount, MN	44.75	-93.07	7.0	820
Mishra et al.	2010	U.S.	Coshocton, Ohio	40.58	-81.79	10.5	999
Mishra et al.	2010	U.S.	South Charleston, Ohio	39.75	-83.60	10.8	1037
Mishra et al.	2010	U.S.	Hoytville, Ohio	41.18	-83.78	9.5	845
Mishra et al.	2010	U.S.	Delaware	40.42	-83.25	13.3	1125
Mishra et al.	2010	U.S.	Coshocton	40.33	-81.84	10.5	999
Mishra et al.	2010	U.S.	Hoytville	41.48	-84.15	9.5	845
Jacinthe & Lal	2009	U.S.	Elnora, Indiana	38.78	-87.08	11.0	973
Blanco-Canqui & Lal	2008	U.S.	Fremont, OH	41.36	-83.09	9.2	837
Blanco-Canqui & Lal	2008	U.S.	Canal Fulton, OH	40.88	-81.64	9.8	935
Blanco-Canqui & Lal	2008	U.S.	Grove City, PA	41.22	-80.08	9.1	948
Blanco-Canqui & Lal	2008	U.S.	Troy, PA	41.32	-76.87	9.9	1034
Blanco-Canqui & Lal	2008	U.S.	Georgetown, KY	38.22	-84.48	12.6	1103
Blanco-Canqui & Lal	2008	U.S.	Glasgow, KY	37.00	-85.93	13.4	1128
Blanco-Canqui & Lal	2008	U.S.	McKee, KY	37.43	-83.60	12.7	1132
Blanco-Canqui & Lal	2008	U.S.	Jackson, OH	38.97	-82.79	10.8	967
Blanco-Canqui & Lal	2008	U.S.	Lewisburg, PA	40.97	-76.93	9.9	1034
Frey & Blevins	1997	U.S.	Lexington, KY	38.12	-84.48	13.0	1140
Black & Tanaka	1997	U.S.	Mandan	46.77	-100.92	5.0	402
Black & Tanaka	1997	U.S.	Mandan	46.77	-100.92	5.0	402
Black & Tanaka	1997	U.S.	Mandan	46.77	-100.92	5.0	402
Black & Tanaka	1997	U.S.	Mandan	46.77	-100.92	5.0	402
Black & Tanaka	1997	U.S.	Mandan	46.77	-100.92	5.0	402
Black & Tanaka	1997	U.S.	Mandan	46.77	-100.92	5.0	402
Havlin & Kissel	1997	U.S.	Kansas	39.12	-96.62	12.8	835
Havlin & Kissel	1997	U.S.	Kansas	39.12	-96.62	12.8	835
Havlin & Kissel	1997	U.S.	Kansas	39.12	-96.62	12.8	835
Matowo et al.	1999	U.S.	Manhattan, KS	39.22	-96.60	11.4	800
Matowo et al.	1999	U.S.	Manhattan, KS	39.22	-96.60	11.4	800
Matowo et al.	1999	U.S.	Manhattan, KS	39.22	-96.60	11.4	800
Matowo et al.	1999	U.S.	Manhattan, KS	39.22	-96.60	11.4	800
Omonode et al.	2006	U.S.	West Lafayette, IN (Purdue Uni	40.57	-86.93	11.0	1043
Omonode et al.	2006	U.S.	West Lafayette, IN (Purdue Uni	40.57	-86.93	11.0	1043
Puget & Lal	2005	U.S.	Columbus, OH	40.08	-83.07	10.5	930
Mestelan	2008	U.S.	Hoytville, Ohio	41.00	-84.00	9.9	845
Mestelan	2008	U.S.	Wooster, Ohio	40.80	-82.00	9.1	905
Chatterjee & Lal	2009	U.S.	Temperence, MI	41.85	-83.53	8.5	838
Chatterjee & Lal	2009	U.S.	Lenawee, MI	41.78	-83.77	8.5	838
Chatterjee & Lal	2009	U.S.	Scioto, OH	39.08	-83.00	10.5	1043
Chatterjee & Lal	2009	U.S.	Canal Fulton, OH	40.90	-81.55	8.5	1068
Chatterjee & Lal	2009	U.S.	Salisbury, PA	39.75	-79.08	9.0	1283
Halvorson et al.	2002	U.S.	Mandan	46.77	-100.95	5.0	418
Halvorson et al.	2002	U.S.	Mandan	46.77	-100.95	5.0	418
Thomas et al.	2007	Australia	Queensland	-28.52	150.37	19.8	620
Sá et al.	2001	Brazil	Ponta Grossa (Frankanna Farm)	-25.33	-50.33	18.7	1545
Freixo et al.	2002	Brazil	Passo Fundo, Rio Grande do Su	-28.25	-52.40	19.4	1746
Freixo et al.	2002	Brazil	Passo Fundo, Rio Grande do Su	-28.25	-52.40	19.4	1746
Roscoe & Buurman	2003	Brazil	Embrapa CNPMS, Sete Lagoas I	-19.43	-44.17	22.1	1340
DeMaria et al.	1999	Brazil		-22.25	-47.07	23.0	1060
Sisti et al.	2004	Brazil	Passo Fundo RS	-28.25	-52.40	19.4	1746
Sisti et al.	2004	Brazil	Passo Fundo RS	-28.25	-52.40	19.4	1746
Sisti et al.	2004	Brazil	Passo Fundo RS	-28.25	-52.40	19.4	1746
Bayer et al.	2000	Brazil	UFRGS, Eldor. Do Sul RS	-30.85	-51.63	19.4	1440
Bayer et al.	2000	Brazil	UFRGS, Eldor. Do Sul RS	-30.85	-51.63	19.4	1440
Zanatta et al.	2007	Brazil	UFRGS, Eldor. Do Sul RS	-30.85	-51.63	19.4	1440
Zanatta et al.	2007	Brazil	UFRGS, Eldor. Do Sul RS	-30.85	-51.63	19.4	1440
Zanatta et al.	2007	Brazil	UFRGS, Eldor. Do Sul RS	-30.85	-51.63	19.4	1440
Zanatta et al.	2007	Brazil	UFRGS, Eldor. Do Sul RS	-30.85	-51.63	19.4	1440

Zanatta et al.	2007	Brazil	UFRGS, Eldor. Do Sul RS	-30.85	-51.63	19.4	1440
Zanatta et al.	2007	Brazil	UFRGS, Eldor. Do Sul RS	-30.85	-51.63	19.4	1440
Metay et al.	2007	Brazil	Goiânia, Goiás	-16.58	-49.35	22.5	1500
Marchão et al.	2009	Brazil	Planaltina, Distrito Federal	-15.65	-47.73	26.0	1500
Calegari et al.	2008	Brazil	Parana State	-26.12	-52.68	18.4	1350
Calegari et al.	2008	Brazil	Parana State	-26.12	-52.68	18.4	1350
Sá et al.	2009	Brazil	Parana	-25.33	-50.33	18.5	1545
Machado et al.	2003	Brazil	Londrina	-23.38	-51.18	20.7	1622
Follett et al.	2005	Mexico	Gelaya, Gto	20.52	-100.82	20.0	598
Follett et al.	2005	Mexico	Gelaya, Gto	20.52	-100.82	20.0	598
Follett et al.	2005	Mexico	Gelaya, Gto	20.52	-100.82	20.0	598
Follett et al.	2005	Mexico	Gelaya, Gto	20.52	-100.82	20.0	598
Follett et al.	2005	Mexico	Gelaya, Gto	20.52	-100.82	20.0	598
Follett et al.	2005	Mexico	Gelaya, Gto	20.52	-100.82	20.0	598
Slavo et al.	2010	Uruguay	Paysandu	-32.35	-58.03	17.0	1200
Chivenge et al.	2007	Zimbabwe	Harare (Institute of Agricultural	-17.72	31.10	22.0	900
Chivenge et al.	2007	Zimbabwe	near Harare (Domboshawa Tra	-17.72	31.10	22.0	900
Gwenzi et al.	2009	Zimbabwe	Lowveld	-20.35	32.35	24.0	482
Shemdoe et al.	2009	Tanzania	Mpwapwa	-6.17	36.43	21.5	575
Zhang et al.	2009	China	Zhangwu, Liaoning	42.53	122.33	7.2	510
Chen et al.	2009	China	Chenghuang, Linfen, Shanxi	38.10	113.00	10.7	555
Jin et al.	2007	China	Luoyang, Henan	34.50	113.00	10.1	746
Shao et al.	2007	China	Chongqing	30.43	106.43	18.3	1105
Gao et al.	2008	China	Chongqing	30.43	106.43	18.3	1105
Liu et al.	2010	China	Linfen, Shanxi	36.13	111.44	10.7	555
Du et al.	2010	China	Luancheng	37.88	114.68	12.2	536
Liang et al.	2011	China	Dehui, Jilin	44.20	125.55	4.4	520
Hou et al.	2012	China	Yucheng	36.83	116.57	13.4	567
Hou et al.	2012	China	Yucheng	36.83	116.57	13.4	567
Abreu	2011	U.S.	Altus, Oklahoma	34.64	-99.33	15.0	741
Abreu	2011	U.S.	Altus, Oklahoma	34.64	-99.33	15.0	741
Abreu	2011	U.S.	Altus, Oklahoma	34.64	-99.33	15.0	741
Abreu	2011	U.S.	Altus, Oklahoma	34.64	-99.33	15.0	741
Abreu	2011	U.S.	Altus, Oklahoma	34.64	-99.33	15.0	741
Abreu	2011	U.S.	Altus, Oklahoma	34.64	-99.33	15.0	741
Abreu	2011	U.S.	Altus, Oklahoma	34.64	-99.33	15.0	741
Abreu	2011	U.S.	Lahoma, Oklahoma	36.39	-98.09	15.6	800
Abreu	2011	U.S.	Ottawa, Miami	36.86	-94.79	14.7	1139
Abreu	2011	U.S.	Noble, Perry1	35.14	-97.40	15.5	929
Abreu	2011	U.S.	Noble, Perry2	35.14	-97.40	15.5	929
Abreu	2011	U.S.	Garfield, Lahoma1	36.39	-98.09	15.5	853
Abreu	2011	U.S.	Garfield, Lahoma2	36.39	-98.09	15.5	853
Abreu	2011	U.S.	Textas, Goodwell	35.14	-97.39	13.1	445
Abreu	2011	U.S.	Washita, Canute	35.10	-98.34	15.5	752
Abreu	2011	U.S.	Cotton, Walters	36.97	-95.86	17.2	841
Jin et al.	2011	China	Gaocheng, Hebei	38.30	114.80	12.5	494
Al-Kaisi et al.	2005	U.S.	Kanawha, IA	42.93	-93.80	7.8	762
Al-Kaisi et al.	2005	U.S.	Sutherland, IA	43.00	-95.50	8.0	711
Al-Kaisi et al.	2005	U.S.	Nashua, IA	43.00	-92.50	8.1	844
Al-Kaisi et al.	2005	U.S.	Armstrong, IA	43.40	-94.50	7.6	784
Al-Kaisi et al.	2005	U.S.	Crawfordsville, IA	41.20	-91.50	10.7	946
Hulugalle & Entwistle	1997	Australia	Narrabri, NSW	-30.33	149.78	18.5	616
Yang et al.	2009	Canada	Elora, Ontario	43.63	-80.42	6.4	900
Yang et al.	2009	Canada	Woodslee, Ontario	42.22	-82.73	8.9	876
Yang et al.	2009	U.S.	Urbana, Illinois	40.10	-88.20	18.6	657
Sun et al.	2011	UK	Invergowrie, Dundee, Scotland	56.45	-3.00	18.0	690
Álvaro-Fuentes et al.	2012	Spain	Agramunt	41.80	1.12	13.8	432
Álvaro-Fuentes et al.	2012	Spain	Agramunt	41.80	1.12	13.8	432
Bhattacharyya et al.	2012	India	Hawalbagh	29.60	79.67	17.8	1017
Follett et al.	2013	U.S.	Fort Collins, CO	40.65	-105.00	9.5	400
Franzluebbers et al.	2013	U.S.	Georgia	33.62	-83.42	16.5	1250
Jemai et al.	2012	Tunisia	Hamrounia region	36.87	9.60	18.2	560
Kumar et al.	2012	U.S.	Wooster	40.42	-83.25	9.1	905

Kumar et al.	2012	U.S.	Hoytville	41.48	-84.15	9.9	845
Lu et al.	2014	China	Linfen	38.10	113.00	10.7	555
Lou et al.	2012	China	Jianping	41.67	119.47	6.5	450
Lou et al.	2012	China	Changtu	42.43	124.20	7.0	608
Mikha et al.	2012	U.S.	Akron, CO	40.15	-103.15	9.6	418
Sá et al.	2013	Brazil	Parana State	-25.15	-50.15	18.5	1545
Toosi et al.	2012	U.S	IA	43.34	-91.58	7.3	832
Araya et al.	2012	Ethiopia	May Zegzeg	13.65	39.17	13.0	741
Getahum et al.	2016	Denmark	Flakkebjerg	55.32	11.38	7.7	558
Villamil et al.	2015	U.S.	DeKalb, Monmouth, Perry and	40.70	-89.60	13.5	902
Villamil et al.	2015	U.S.	DeKalb, Monmouth, Perry and	40.70	-89.60	13.5	902
Villamil et al.	2015	U.S.	DeKalb, Monmouth, Perry and	40.70	-89.60	13.5	902
Kibet et al.	2016	U.S.	Lincoln	40.93	-96.47	10.9	693
Page et al.	2013	Australia	Biloela, Queensland	-24.38	150.51	22.0	627
Page et al.	2013	Australia	Hermitage, Queensland	-28.21	152.10	17.5	701
Page et al.	2013	Australia	Goodger, Queensland	-26.64	151.84	18.8	753
Jemai et al.	2013	Tunisia	Mateur	36.87	9.60	18.2	650
Hati et al.	2015	India	Bhopal	23.30	77.40	24.5	1130
Sainju et al.	2015	U.S.	Montana	48.55	-104.83	7.5	340
Wang et al.	2008	China	Linfen, Shanxi	38.10	113.00	10.7	555
Shrestha et al.	2015	Norway	Ås	59.66	10.77	5.0	785
Muhlbachová et al.	2015	Czech	Prague-Ruzyně	50.08	14.33	8.4	472
Muhlbachová et al.	2015	Czech	Prague-Ruzyně	50.08	14.33	8.4	472
Chaudhary et al.	2015	India	Varanasi	25.30	80.50	26.0	1081
Huang et al.	2015	China	Beiqiu,YellowRiver Delta	38.25	118.08	13.5	600
Zuber et al.	2015	U.S.	Northwest of Monmouth, IL	40.93	-90.73	17.0	987
Liu et al.	2016	Australia	North East of Moree	-29.13	150.12	19.4	610
Blanco-Moure et al.	2016	Spain	Peñaflor	41.74	-0.77	14.5	355
Blanco-Moure et al.	2016	Spain	Peñaflor	41.74	-0.78	14.5	355
Blanco-Moure et al.	2016	Spain	Lanaja	41.72	-0.36	14.7	433
Blanco-Moure et al.	2016	Spain	Torres de Alcanadre	41.97	-0.08	14.8	468
Blanco-Moure et al.	2016	Spain	Undués de Lerda	42.56	-1.12	14.2	676
Blanco-Moure et al.	2016	Spain	Artieda	42.60	-1.00	14.2	741
Engel et al.	2017	USA	Montana	45.67	-111.15	6.7	411
Kushwa et al.	2016	India	Bhopal	23.30	77.40	24.5	1130
Si et al.	2017	China	Shouyang	37.90	113.17	7.4	463
Singh et al.	2016	Inida	New Delhi	28.67	77.20	22.5	650
Singh et al.	2016	Inida	New Delhi	28.67	77.20	22.5	650
Parihar et al.	2016	Inida	New Delhi	28.67	77.20	22.5	650
Parihar et al.	2016	Inida	New Delhi	28.67	77.20	22.5	650
Parihar et al.	2016	Inida	New Delhi	28.67	77.20	22.5	650
Parihar et al.	2016	Inida	New Delhi	28.67	77.20	22.5	650
Guardia et al.	2016	Spain	Madrid	40.53	-3.33	13.5	403
Somasundaram et al.	2017	Australia	Queensland	-28.20	152.10	17.5	685
Somasundaram et al.	2017	Australia	Queensland	-28.20	152.10	17.5	685
Sapkota et al.	2017	India	Bihar	25.58	85.40	26.0	1344
Sá et al.	2015	Brazil	Paraná State	-25.15	-50.15	18.5	1545
Moussadek et al.	2014	Morocco	Merchouch plateau	33.57	-6.70	17.1	450
Moussadek et al.	2014	Morocco	Merchouch plateau	33.57	-6.70	17.1	450
Moussadek et al.	2014	Morocco	Merchouch plateau	33.57	-6.70	17.1	450
Badagliacca et al.	2019	Italy	Sicily	37.50	13.50	15.6	572
Badagliacca et al.	2019	Italy	Sicily	37.50	13.50	15.6	572
Zhang et al.	2018	China	Jilin	44.20	125.60	4.4	520
Zhang et al.	2018	China	Jilin	44.20	125.60	4.4	520
Hernandez et al.	2019	U.S.	Wooster	40.75	-83.75	9.9	1018
Hernandez et al.	2019	U.S.	Hoytville	41.22	-83.75	10.7	874
Parihar et al.	2019	Inida	New Delhi	28.63	77.18	24.3	707
Veloso et al.	2018	Brazil	Eldorado do Sul-RS	-30.10	-51.67	19.4	1440
Veloso et al.	2018	Brazil	Eldorado do Sul-RS	-30.10	-51.67	19.4	1440
Veloso et al.	2018	Brazil	Eldorado do Sul-RS	-30.10	-51.67	19.4	1440
Veloso et al.	2018	Brazil	Eldorado do Sul-RS	-30.10	-51.67	19.4	1440
Veloso et al.	2018	Brazil	Eldorado do Sul-RS	-30.10	-51.67	19.4	1440
Veloso et al.	2018	Brazil	Eldorado do Sul-RS	-30.10	-51.67	19.4	1440

Tiecher et al.	2012	Brazil	Parana State	-26.12	-52.68	18.4	1350
Maillard et al.	2018	Canada	Saskatchewan	50.27	-107.73	3.3	334
Maillard et al.	2018	Canada	Saskatchewan	50.27	-107.73	3.3	334
Maillard et al.	2018	Canada	Saskatchewan	50.27	-107.73	3.3	334
Maillard et al.	2018	Canada	Saskatchewan	50.27	-107.73	3.3	334
Chatterjee et al.	2018	US	North Dakota	45.97	-97.55	5.8	569
Chatterjee et al.	2018	US	North Dakota	45.97	-97.55	5.8	569
Chatterjee et al.	2018	US	North Dakota	45.97	-97.55	5.8	569
Carr et al.	2015	US	North Dakato	45.88	-102.82	5.8	472

AI_{Lang}	Clay%	Silt%	Sand%	pH	Initial yea	Duration (yea	Crops in rotation	Yield-CT	Yield-NT
30.8	18	24	42	5.2	1992	5	barley, chick pea	na.	na.
30.8	18	24	42	5.2	1992	6	barley, chick pea	na.	na.
30.8	18	24	42	5.2	1992	7	barley, chick pea	na.	na.
30.8	18	24	42	5.2	1992	8	barley, chick pea	na.	na.
30.8	18	24	42	5.2	1992	9	barley, chick pea	na.	na.
30.8	18	24	42	5.2	1992	10	barley, chick pea	na.	na.
30.8	18	24	42	5.2	1992	11	barley, chick pea	na.	na.
30.8	18	24	42	5.2	1992	12	barley, chick pea	na.	na.
30.8	18	24	42	5.2	1992	13	barley, chick pea	na.	na.
30.8	18	24	42	5.2	1992	14	barley, chick pea	na.	na.
30.8	18	24	42	5.2	1992	15	barley, chick pea	na.	na.
30.8	18	24	42	5.2	1992	16	barley, chick pea	na.	na.
32.8	25	42	67	7.9	1985	6	winter wheat, vetch, forage pea	na.	na.
32.8	25	42	67	7.9	1985	11	winter wheat, vetch, forage pea	na.	na.
32.8	25	42	67	7.9	1985	13	winter wheat, vetch, forage pea	na.	na.
32.8	25	42	67	7.9	1985	15	winter wheat, vetch, forage pea	na.	na.
32.8	25	42	67	7.9	1985	17	winter wheat, vetch, forage pea	na.	na.
32.8	25	42	67	7.9	1985	18	winter wheat, vetch, forage pea	na.	na.
32.8	25	42	67	7.9	1985	19	winter wheat, vetch, forage pea	na.	na.
32.8	25	42	67	7.9	1985	20	winter wheat, vetch, forage pea	na.	na.
32.8	25	42	67	7.9	1985	11	winter wheat, vetch	na.	na.
32.8	25	42	67	7.9	1983	13	wheat, barley	na.	na.
34.2	17	46	64	8.3	2005	18	Wheat, Barly, Rapeseed	na.	na.
30.3	18	52	70	8.5	2005	15	wheat, barley	na.	na.
26.9	22	46	68	8.2	2005	16	Barley	na.	na.
26.9	22	46	68	8.2	2005	16	Barley	na.	na.
30.8	54	25	79	6.7	1982	8	Wheat, Sunflower, Legumes	1.93	1.98
30.8	54	25	79	6.7	1982	19	Wheat, Sunflower, Legumes	na.	na.
140.8	21	39	60	6.4	1987	19	Wheat, Maize, Canola	na.	na.
54.8	23	37	60	6.4	1988	7	Maize	na.	na.
54.8	23	37	60	6.4	1988	7	Maize, Soybean	na.	na.
140.7	15	49	64	6.5	na.	19	Maize, Soybean, Wheat	na.	na.
140.7	15	49	64	6.5	na.	19	Maize, Soybean, Wheat	na.	na.
140.7	15	49	64	6.5	na.	19	Maize, Soybean, Wheat	na.	na.
174.6	36	43	80	6.3	1992	13	Maize, Soybean	na.	na.
-422.2	15	28	43	6.4	1993	11	Pea, Wheat, Canola	na.	na.
-422.2	15	28	43	6.4	1993	7	Pea, Wheat, Canola	na.	na.
151.7	26	39	65	5.8	1995	7	Maize	na.	na.
95.1	36	44	80	5.5	1993	16	Maize, Soybean, Wheat	na.	na.
158.3	14	44	59	5.7	1976	25	Maize, Soybean	6.48	6.77
141.7	17	56	73	7.3	2000	6	Maize, Soybean, Wheat	na.	na.
33.8	37	43	80	7.1	na.	10	Wheat	na.	na.
33.8	37	43	80	7.1	na.	10	Wheat	na.	na.
33.8	37	43	80	7.1	na.	10	Sorghum	na.	na.
33.8	37	43	80	7.1	na.	10	Sorghum	na.	na.
45.3	56	39	95	4.8	na.	10	Wheat	na.	na.
45.3	56	39	95	4.8	na.	10	Wheat	na.	na.
45.3	56	39	95	4.8	na.	10	Sorghum	na.	na.
45.3	56	39	95	4.8	na.	10	Sorghum	na.	na.
30.0	24	21	44	8.2	na.	15	Maize, Cotton	na.	na.
26.1	23	21	43	7.9	1992	9	Maize, Cotton	na.	na.
49.0	43	45	89	8.2	1982	20	Sorghum, Wheat, Soybean	na.	na.
49.0	43	45	89	8.2	1982	20	Wheat, Soybean	na.	na.
49.0	43	45	89	8.2	1982	20	Soybean	na.	na.
35.3	23	63	85	6.5	1986	11	Maize, Soybean	na.	na.
35.2	25	65	89	5.5	1988	7	Maize, Soybean	na.	na.
35.2	25	65	89	5.5	1988	8	Maize, Soybean	na.	na.
35.2	17	77	94	7.4	1988	12	Maize, Soybean	na.	na.
102.2	17	33	49	5.6	1989	14	Maize, Soybean, Wheat	na.	na.
104.8	38	59	97	6.6	na.	10	Maize, Soybean	na.	na.
137.3	23	55	78	6.3	1990	10	Maize, Soybean	na.	na.
137.3	23	55	78	6.3	1990	15	Maize, Soybean	na.	na.

79.2	19	64	83	6.4	1975	28	Maize, Soybean	na.	na.
137.3	23	55	78	5.5	1991	16	Maize, Soybean	na.	na.
117.1	23	55	78	6.5	1980	23	Maize, Soybean	na.	na.
117.1	23	55	78	6.5	1980	23	Maize, Soybean	na.	na.
117.1	23	55	78	6.5	1980	23	Maize, Soybean	na.	na.
117.1	23	55	78	6.5	1980	23	Maize, Soybean	na.	na.
95.1	14	69	83	5.7	1964	42	Maize	na.	na.
96.0	20	65	85	6.5	1962	44	Maize, Soybean	na.	na.
88.9	40	39	79	6.6	1963	43	Maize, Soybean	na.	na.
84.6	26	60	86	6.4	1986	20	Maize, Soybean, Wheat	na.	na.
95.1	25	53	78	5.8	1986	20	Maize, Alfalfa	na.	na.
88.9	36	26	62	6.6	2000	6	Maize, Soybean, Wheat	na.	na.
88.5	20	43	62	5.2	1993	12	Maize, Soybean	na.	na.
91.0	28	50	78	6.3	na.	15	Maize, Soybean	na.	na.
95.4	20	60	80	6.0	na.	15	Maize, Soybean	na.	na.
104.2	17	52	68	5.4	na.	10	Maize, Soybean	na.	na.
104.4	17	52	69	5.4	na.	20	Maize	na.	na.
87.3	21	56	77	6.3	na.	8	Maize, Soybean, Pumpkin	na.	na.
84.2	21	63	84	5.3	na.	10	Maize, Soybean	na.	na.
89.1	10	28	38	8.5	na.	15	Corn silage, Tobacco, Wheat, Rye	na.	na.
89.5	17	66	83	5.8	na.	12	Maize, Soybean, Alfalfa	na.	na.
104.4	26	52	78	5.8	na.	5	Maize, Soybean	na.	na.
87.7	21	56	77	6.3	1970	20	Maize	7.11	5.79
80.4	21	58	79	7.0	1983	6	Wheat	1.21	1.16
80.4	21	58	79	7.0	1983	6	Wheat	1.19	1.17
80.4	21	58	79	7.0	1983	6	Wheat	1.16	1.16
80.4	21	58	79	7.0	1983	6	Wheat, Sunflower	2.06	2.26
80.4	21	58	79	7.0	1983	6	Wheat, Sunflower	2.16	2.21
80.4	21	58	79	7.0	1983	6	Wheat, Sunflower	2.25	2.59
65.2	33	48	80	7.0	1975	11	Sorghum	5.53	5.26
65.2	33	48	80	7.0	1975	11	Sorghum	1.62	1.86
65.2	33	48	80	7.0	1975	11	Sorghum, Soybean	3.44	4.08
70.2	25	57	82	6.6	1982	10	Sorghum	3.07	3.43
70.2	25	57	82	6.6	1982	10	Sorghum	4.75	4.94
70.2	25	57	82	6.6	1982	10	Sorghum	5.81	5.51
70.2	25	57	82	6.6	1982	10	Sorghum	6.65	6.55
94.8	27	60	87	6.5	1980	24	Maize, Soybean	na.	na.
94.8	27	60	87	6.5	1998	6	Maize, Soybean	na.	na.
88.6	23	53	76	6.4	1993	8	Maize, Soybean	na.	na.
85.4	28	50	78	6.3	1996	9	Maize	na.	na.
99.5	17	53	70	5.7	1993	10	Maize	na.	na.
98.5	15	24	39	6.5	1998	10	Maize, Soybean, Wheat	na.	na.
98.5	39	34	73	6.6	1998	10	Maize, Soybean, Wheat	na.	na.
99.3	23	44	67	6.5	1993	15	Maize, Soybean	na.	na.
125.6	15	49	64	5.8	2002	6	Maize, Soybean	na.	na.
142.5	22	52	74	4.8	1978	30	Alfalfa	na.	na.
83.6	21	58	79	7.0	1984	12	Wheat	na.	na.
83.6	21	58	79	7.0	1984	12	Wheat, Sunflower	na.	na.
31.3	53	19	72	7.5	1988	8	Wheat	na.	na.
82.6	57	23	79	4.5	1976	22	Soybean, Maize, Wheat, Oat, Lupine	na.	na.
90.0	50	16	66	4.5	1987	11	Wheat, Soybean	na.	na.
90.0	50	16	66	4.5	1987	11	Wheat, Soybean, Vetch, Maize	na.	na.
60.6	37	5	42	4.8	na.	10	Maize, Bean	na.	na.
46.1	39	10	49	5.3	1986	9	Soybean, Oat, Maize	3.83	3.76
90.0	50	16	66	4.5	1985	13	Wheat, Soybean	4.54	4.72
90.0	50	16	66	4.5	1985	13	Wheat, Soybean, Vetch, Maize	4.54	5.95
90.0	50	16	66	4.5	1985	13	Wheat, Soybean, Vetch, Maize	na.	na.
74.2	16	39	54	5.1	1985	9	Oat, Maize	na.	na.
74.2	16	39	54	5.1	1985	9	Oat, Vetch, Maize, Cowpea	na.	na.
74.2	16	39	54	5.1	1985	18	Oat, Maize	na.	na.
74.2	16	39	54	5.1	1985	18	Vetch, Maize	na.	na.
74.2	16	39	54	5.1	1985	18	Oat, Vetch, Maize, Cowpea	na.	na.
74.2	16	39	54	5.1	1985	18	Oat, Maize	na.	na.

74.2	16	39	54	5.1	1985	18	Vetch, Maize	na.	na.
74.2	16	39	54	5.1	1985	18	Oat, Vetch, Maize, Cowpea	na.	na.
66.7	38	17	55	5.2	1998	5	Rice, Soybean	na.	na.
57.7	62	8	69	5.0	na.	10	Soybean, Maize	na.	na.
73.6	62	25	87	5.3	1986	19	Maize, Soybean	3.64	3.85
73.6	62	25	87	5.3	1986	19	Maize, Soybean	3.64	3.85
83.5	57	23	79	4.5	1976	22	Soybean, Maize, Wheat, Oat, Lupine, Rye	na.	na.
78.4	62	25	87	5.3	1976	22	Soybean, Wheat, Maize, Cotton	na.	na.
29.9	39	24	64	7.1	1994	5	Wheat, Maize	4.50	4.60
29.9	39	24	64	7.1	1994	5	Wheat, Maize	9.60	9.10
29.9	39	24	64	7.1	1994	5	Wheat, Maize	14.40	13.20
29.9	39	24	64	7.1	1994	5	Wheat, Bean	5.20	4.19
29.9	39	24	64	7.1	1994	5	Wheat, Bean	7.20	6.85
29.9	39	24	64	7.1	1994	5	Wheat, Bean	8.20	7.84
70.6	41	28	69	6.8	1993	10	Barley, Sorghum, Wheat, Sunflower, Oat,	na.	na.
40.9	51	19	71	6.1	1988	10	Maize	na.	na.
40.9	51	19	71	6.1	1988	10	Maize	na.	na.
20.1	20	10	30	7.6	2000	5	Wheat, Cotton	7.79	7.15
26.7	49	16	65	6.2	2002	5	Sorghum	na.	na.
70.8	6	15	21	7.8	2002	6	Maize	na.	na.
51.9	20	34	54	8.0	na.	11	Wheat	na.	na.
73.9	15	43	58	7.6	1999	6	Wheat	4.52	4.67
60.4	22	43	65	6.6	1989	10	Rice, Wheat	na.	na.
60.4	22	43	65	6.6	1991	13	Rice, Rape	na.	na.
51.9	21	52	73	8.0	1992	14	Wheat	na.	na.
43.9	7	19	26	7.5	2001	7	Wheat, Maize	na.	na.
118.3	24	52	77	6.5	2001	5	Maize	na.	na.
42.3	11	63	74	7.9	2003	6	Wheat, Maize	na.	na.
42.3	11	63	74	7.9	2003	6	Wheat, Maize	na.	na.
49.4	8	17	25	5.8	2002	8	Cotton, Wheat, Sorghum	na.	na.
49.4	8	17	25	5.8	2002	8	Wheat, Cotton	na.	na.
49.4	8	17	25	5.8	2002	8	Cotton, Sorghum	na.	na.
49.4	8	17	25	5.8	2002	8	Wheat, Soybean, Sorghum, Cotton	na.	na.
49.4	8	17	25	5.8	2002	8	Cotton	na.	na.
49.4	8	17	25	5.8	2002	8	Wheat	na.	na.
49.4	8	17	25	5.8	2002	8	Sorghum	na.	na.
51.3	20	30	50	4.9	2005	5	Wheat	na.	na.
77.5	18	46	64	5.8	na.	5	Soybean, Maize, Wheat	na.	na.
59.9	14	42	56	5.1	na.	7	Wheat, Soybean, Maize	na.	na.
59.9	14	42	56	5.1	na.	5	Maize, Wheat	na.	na.
55.0	20	30	50	4.9	na.	12	Wheat	na.	na.
55.0	20	30	50	4.9	na.	5	Wheat	na.	na.
34.1	14	42	56	5.1	na.	5	Wheat, Sorghum	na.	na.
48.5	18	42	60	6.6	na.	18	Cotton	na.	na.
48.9	21	63	84	6.4	na.	12	Wheat	na.	na.
39.5	7	19	26	7.4	1998	11	Wheat, Maize	15.75	16.10
97.7	27	43	70	7.1	na.	7	Maize, Soybean	11.17	10.55
88.9	36	54	90	6.6	na.	7	Maize, Soybean	9.13	8.50
104.2	23	36	59	6.5	na.	7	Maize, Soybean	13.23	12.76
103.0	27	44	71	7.0	na.	7	Maize, Soybean	12.68	13.30
88.7	30	53	83	6.4	na.	7	Maize, Soybean	12.63	12.31
33.3	53	21	74	7.5	1985	9	Wheat, Cotton	na.	na.
141.7	15	41	56	6.5	na.	23	Maize	na.	na.
98.4	36	44	80	5.5	na.	16	Maize, Soybean	na.	na.
35.3	23	63	85	6.5	na.	11	Maize, Soybean	na.	na.
38.3	21	38	60	6.0	2003	5	Barley	na.	na.
31.3	20	42	62	8.0	1999	11	Barley, Wheat	na.	na.
31.3	20	42	62	8.0	1990	20	Barley, Wheat	na.	na.
57.1	36	30	65	5.1	2001	9	Rice, Wheat	na.	na.
42.1	25	30	55	7.4	2001	8	Maize	na.	na.
75.8	25	19	44	5.4	2002	5	Sorghum, Soybean, Maize, Wheat, Rye, M	na.	na.
30.8	39	31	70	7.3	2000	7	Wheat, Sulla	na.	na.
99.5	28	51	79	6.4	1962	49	Maize, Soybean	12.00	11.40

85.4	39	34	73	6.6	1964	47	Maize, Soybean	9.10	9.30
51.9	17	45	62	8.3	1992	17	Wheat	3.54	4.64
69.2	15	40	55	7.8	1998	12	Maize	4.40	6.19
86.9	19	42	61	6.3	2005	5	Maize	5.75	6.44
43.5	25	47	72	6.0	1967	39	Wheat	na.	na.
83.5	10	4	14	6.7	na.	29	Soybean, Maize, Wheat, Vetch	na.	na.
114.0	28	50	78	7.3	1987	23	Maize, Soybean, Wheat	na.	na.
57.0	43	31	74	6.6	2005	5	Wheat, Grass pea, Barley	na.	na.
72.5	15	14	29	6.3	2002	11	Wheat, Barley, Pea, Oat	na.	na.
66.8	21	53	74	6.6	2005	8	Maize	na.	na.
66.8	21	53	74	6.6	2005	8	Maize	na.	na.
66.8	21	53	74	6.6	2005	8	Maize	na.	na.
63.7	30	52	82	6.3	1981	33	Sorghum, Soybean, Maize	na.	na.
28.5	41	22	63	7.8	1984	26	Wheat, Sorghum	na.	na.
40.1	62	16	78	7.0	1981	27	Wheat	na.	na.
40.1	62	16	78	5.8	1994	16	Wheat, Legume	na.	na.
35.7	39	31	70	7.3	2000	7	Wheat, Sulla	na.	na.
46.1	52	29	81	7.5	2000	6	Wheat, Soybean	3.05	3.70
45.3	25	43	68	7.7	1984	29	Wheat	na.	na.
51.9	34	43	77	8.1	1992	14	Wheat	4.00	4.37
157.0	13	42	55	5.1	1983	26	Barley, Wheat	na.	na.
56.2	20	41	61	6.3	1995	14	Pea, Wheat, Rape	2.00	2.20
56.2	20	41	61	6.3	1995	18	Pea, Wheat, Rape	2.10	2.20
41.6	25	16	41	6.9	2003	7	Rice, Wheat	na.	na.
44.4	22	66	88	8.3	2003	9	Wheat, Maize	na.	na.
58.1	24	69	93	6.2	1996	16	Maize, Soybean, Wheat	na.	na.
31.5	42	20	62	6.8	1998	15	Wheat, Chickpea	na.	na.
24.5	25	42	67	7.9	na.	19	Barly	na.	na.
24.5	25	42	67	7.9	na.	20	Barly	na.	na.
29.5	23	39	62	8.1	na.	14	Barly	na.	na.
31.6	21	41	62	8.1	na.	9	Barly	na.	na.
47.6	49	32	81	8.2	na.	13	Barly	na.	na.
52.2	31	25	56	7.4	na.	19	Barly	na.	na.
61.3	10	81	91	9.0	2002	10	Wheat	na.	na.
46.1	52	29	81	7.5	2000	12	Soybean, Wheat	3.92	3.86
62.5	12	41	53	8.2	2004	7	Maize	7.75	7.03
28.9	19	35	54	9.1	2006	5	Rice, Maize	8.32	8.55
28.9	19	35	54	9.1	2006	5	Rice, Maize	8.72	9.17
28.9	19	35	54	9.1	2008	7	Maize, Wheat, Mungbean	4.58	4.58
28.9	19	35	54	9.1	2008	7	Maize, Chickpea, Sesbaina	3.43	3.43
28.9	19	35	54	9.1	2008	7	Maize, Mustard, Mungbean	5.33	8.00
28.9	19	35	54	9.1	2008	7	Maize, Sesbania	na.	na.
29.8	31	25	56	7.4	1994	18	Legume, Wheat, Vetch, Barley	na.	na.
39.1	62	16	78	7.0	1968	47	Cereal crops	na.	na.
39.1	62	16	78	7.0	1968	47	Cereal crops	na.	na.
51.7	27	47	74	8.3	2006	7	Rice, Wheat	na.	na.
83.5	10	4	14	6.7	na.	29	Soybean, Oat, Maize, Wheat, Vetch	na.	na.
26.3	32	32	64	6.7	2006	5	Wheat, Lentil	na.	na.
26.3	32	32	64	6.7	2006	5	Wheat, Lentil	na.	na.
26.3	32	32	64	6.7	2006	5	Wheat, Lentil	na.	na.
36.7	31	56	87	7.6	1991	23	Wheat	na.	na.
36.7	31	56	87	7.6	1991	23	Wheat, Fafa bean	na.	na.
118.2	23	49	72	6.8	2001	12	Maize	6.21	6.25
118.2	23	49	72	6.8	2001	12	Maize, Soybean	9.35	9.28
102.8	28	51	79	6.4	1962	52	Maize, Soybean	na.	na.
81.7	39	34	73	6.6	1964	50	Maize, Soybean	na.	na.
29.1	19	35	54	9.1	2012	5	Maize, Wheat, Mungbean	na.	na.
74.2	26	25	51	5.0	1985	29	Oat, Maize	na.	na.
74.2	26	25	51	5.0	1985	29	Vetch, Maize	na.	na.
74.2	26	25	51	5.0	1985	29	Oat, Vetch, Maize, Cowpea	na.	na.
74.2	26	25	51	5.0	1985	29	Oat, Maize	na.	na.
74.2	26	25	51	5.0	1985	29	Vetch, Maize	na.	na.
74.2	26	25	51	5.0	1985	29	Oat, Vetch, Maize, Cowpea	na.	na.

73.6	62	25	87	5.3	1986	23	Maize, Soybean, Winter crops	na.	na.
101.2	23	44	67	6.9	1982	16	Wheat	na.	na.
101.2	23	44	67	6.9	1982	21	Wheat, Pea, Chickpea, Lentil	na.	na.
101.2	23	44	67	6.9	1982	25	Wheat, Pea, Chickpea, Lentil	na.	na.
101.2	23	44	67	6.9	1982	29	Wheat, Pea, Chickpea, Lentil	na.	na.
98.1	11	53	64	7.7	na.	20	Maize, Soybean	na.	na.
98.1	11	53	64	7.7	na.	36	Maize, Soybean	na.	na.
98.1	11	53	64	7.7	na.	20	Maize, Soybean	na.	na.
81.7	18	27	44	7.0	1993	20	Wheat, Pea, Canola, Legume, barley, Mai	na.	na.

Replicates	Legume/cover	Rotation(n	Annual crop	ΔCinput	N input	SOC stock	Bulk density	SOC content	Maximum de
3	yes	2	1	na.	yes	yes	na.	na.	30
3	yes	2	1	na.	yes	yes	na.	na.	30
3	yes	2	1	na.	yes	yes	na.	na.	30
3	yes	2	1	na.	yes	yes	na.	na.	30
3	yes	2	1	na.	yes	yes	na.	na.	30
3	yes	2	1	na.	yes	yes	na.	na.	30
3	yes	2	1	na.	yes	yes	na.	na.	30
3	yes	2	1	na.	yes	yes	na.	na.	30
3	yes	2	1	na.	yes	yes	na.	na.	30
3	yes	2	1	na.	yes	yes	na.	na.	30
3	yes	2	1	na.	yes	yes	na.	na.	30
3	yes	2	1	na.	yes	yes	na.	na.	30
4	yes	2	1	na.	yes	yes	na.	yes	40
4	yes	2	1	na.	yes	yes	na.	yes	40
4	yes	2	1	na.	yes	yes	na.	yes	40
4	yes	2	1	na.	yes	yes	na.	yes	40
4	yes	2	1	na.	yes	yes	na.	yes	40
4	yes	2	1	na.	yes	yes	na.	yes	40
4	yes	2	1	na.	yes	yes	na.	yes	40
4	yes	2	1	na.	yes	yes	na.	yes	40
4	yes	2	1	na.	yes	yes	na.	na.	40
4	no/na.	2	1	na.	yes	yes	na.	na.	40
3	no/na.	3	1	na.	na.	yes	yes	na.	40
4	no/na.	2	1	na.	na.	yes	yes	na.	40
3	no/na.	1	1	na.	na.	yes	yes	na.	40
3	no/na.	1	1	na.	na.	yes	yes	na.	40
4	yes	3	1	na.	yes	na.	yes	yes	52
4	yes	3	1	na.	yes	na.	yes	yes	52
4	no/na.	3	1	na.	na.	yes	yes	yes	40
3	no/na.	1	1	na.	yes	yes	yes	yes	40
3	yes	2	1	na.	na.	yes	yes	yes	40
3	yes	3	1	na.	na.	yes	na.	yes	60
3	yes	3	1	na.	na.	yes	na.	yes	60
3	yes	3	1	na.	na.	yes	na.	yes	60
4	yes	2	1	yes	yes	na.	na.	yes	60
4	yes	3	1	yes	yes	na.	na.	yes	30
4	yes	3	1	na.	yes	na.	na.	yes	30
3	no/na.	1	1	na.	na.	na.	yes	yes	30
4	yes	3	1	na.	na.	yes	yes	yes	30
4	yes	2	1	na.	na.	yes	yes	yes	60
3	yes	3	1	yes	yes	na.	yes	yes	50
3	no/na.	1	1	yes	na.	na.	yes	yes	65
3	no/na.	1	1	yes	yes	na.	yes	yes	65
3	no/na.	1	1	yes	na.	na.	yes	yes	65
3	no/na.	1	1	yes	yes	na.	yes	yes	65
4	no/na.	1	1	yes	yes	na.	yes	yes	65
4	no/na.	1	1	yes	yes	na.	yes	yes	65
4	no/na.	1	1	yes	yes	na.	yes	yes	65
4	no/na.	1	1	yes	yes	na.	yes	yes	65
4	no/na.	2	1	yes	yes	na.	yes	yes	50
4	no/na.	2	2	na.	yes	na.	na.	yes	30
4	yes	3	2	yes	yes	na.	na.	yes	105
4	yes	2	2	yes	yes	na.	na.	yes	105
4	yes	1	1	yes	na.	na.	na.	yes	105
3	yes	2	2	yes	na.	na.	yes	yes	90
6	yes	2	1	na.	yes	na.	yes	yes	30
6	yes	2	1	na.	yes	na.	yes	yes	30
6	yes	2	1	na.	yes	na.	yes	yes	75
3	yes	3	1	na.	yes	na.	yes	yes	100
5	yes	2	2	na.	na.	na.	yes	yes	30
6	yes	2	2	na.	yes	na.	yes	yes	60
6	yes	2	2	na.	yes	na.	yes	yes	60

4	yes	2	1	na.	yes	na.	yes	yes	100
3	yes	2	1	na.	yes	na.	yes	yes	30
3	yes	2	1	na.	na.	na.	yes	yes	45
3	yes	2	1	na.	na.	na.	yes	yes	45
3	yes	2	1	na.	yes	na.	yes	yes	45
3	yes	2	1	na.	yes	na.	yes	yes	45
4	no/na.	1	1	na.	na.	na.	yes	yes	40
4	yes	2	1	na.	na.	na.	yes	yes	40
4	yes	2	1	na.	na.	na.	yes	yes	40
4	yes	3	1	na.	na.	na.	yes	yes	40
4	no/na.	2	1	na.	na.	na.	yes	yes	40
4	yes	3	1	na.	na.	na.	yes	yes	40
3	yes	2	1	yes	na.	na.	yes	yes	40
3	yes	3	1	na.	yes	na.	yes	yes	60
3	yes	2	1	na.	yes	na.	yes	yes	60
3	yes	2	1	na.	yes	na.	yes	yes	60
3	no/na.	1	1	na.	yes	na.	yes	yes	60
3	yes	3	1	na.	yes	na.	yes	yes	60
3	yes	2	1	na.	yes	na.	yes	yes	60
3	no/na.	3	1	na.	yes	na.	yes	yes	60
3	yes	3	1	na.	yes	na.	yes	yes	60
3	yes	2	1	na.	yes	na.	yes	yes	60
3	no/na.	1	1	na.	na.	na.	yes	yes	30
3	no/na.	1	1	yes	na.	na.	yes	yes	91
3	no/na.	1	1	yes	yes	na.	yes	yes	91
3	no/na.	1	1	yes	yes	na.	yes	yes	91
3	no/na.	1	2	yes	yes	na.	yes	yes	91
3	no/na.	1	2	yes	yes	na.	yes	yes	91
3	no/na.	2	2	yes	yes	na.	yes	yes	91
3	no/na.	1	1	yes	na.	na.	na.	yes	30
3	yes	1	1	yes	na.	na.	na.	yes	30
3	yes	2	1	yes	na.	na.	na.	yes	30
3	no/na.	1	1	na.	na.	na.	na.	yes	40
3	no/na.	1	1	na.	yes	na.	na.	yes	40
3	no/na.	1	1	na.	yes	na.	na.	yes	40
3	no/na.	1	1	na.	yes	na.	na.	yes	40
4	yes	2	1	na.	na.	na.	yes	yes	100
4	yes	2	1	na.	na.	na.	yes	yes	100
4	yes	2	1	yes	na.	na.	yes	yes	80
4	no/na.	2	1	na.	na.	na.	na.	yes	45
4	no/na.	2	1	na.	na.	na.	na.	yes	45
3	yes	3	2	na.	yes	na.	yes	yes	60
3	yes	3	2	na.	yes	na.	yes	yes	60
3	yes	2	1	na.	yes	na.	yes	yes	60
3	yes	2	1	na.	yes	na.	yes	yes	60
3	no/na.	1	1	na.	yes	na.	yes	yes	60
3	no/na.	1	1	yes	yes	na.	yes	yes	30
3	no/na.	2	2	yes	yes	na.	yes	yes	30
3	no/na.	1	1	na.	yes	yes	yes	na.	30
3	yes	3	2	yes	yes	na.	yes	yes	40
3	yes	2	2	na.	yes	na.	yes	yes	30
3	yes	3	2	na.	yes	na.	yes	yes	30
3	yes	2	1	yes	na.	na.	yes	yes	45
2	yes	3	2	na.	yes	na.	na.	yes	30
3	yes	2	2	yes	yes	na.	yes	yes	100
3	yes	3	2	yes	yes	na.	yes	yes	100
3	yes	3	2	yes	yes	na.	yes	yes	100
3	no/na.	2	2	na.	na.	yes	na.	na.	30
3	yes	2	2	na.	na.	yes	na.	na.	30
3	no/na.	2	2	yes	na.	na.	na.	yes	30
3	no/na.	2	2	yes	na.	na.	na.	yes	30
3	yes	4	2	yes	na.	na.	na.	yes	30
3	no/na.	2	2	yes	yes	na.	na.	yes	30

3	no/na.	2	2	yes	yes	na.	na.	yes	30
3	yes	4	2	yes	yes	na.	na.	yes	30
6	yes	2	2	na.	yes	na.	yes	yes	30
na..	yes	3	1	na.	yes	na.	yes	yes	30
3	yes	2	1	na.	yes	na.	yes	yes	60
3	yes	3	2	na.	yes	na.	yes	yes	60
5	yes	3	2	yes	yes	na.	na.	yes	40
3	yes	3	2	na.	na.	yes	yes	yes	40
4	no/na.	2	2	yes	na.	yes	na.	yes	30
4	no/na.	2	2	yes	yes	yes	na.	yes	30
4	no/na.	2	2	yes	yes	yes	na.	yes	30
4	yes	2	2	yes	na.	yes	na.	yes	30
4	yes	2	2	yes	yes	yes	na.	yes	30
4	yes	2	2	yes	yes	yes	na.	yes	30
3	yes	7	2	na.	na.	na.	na.	yes	80
3	no/na.	1	1	na.	yes	na.	na.	yes	30
3	no/na.	1	1	na.	yes	na.	na.	yes	30
3	no/na.	2	2	na.	yes	na.	yes	yes	60
6	no/na.	1	1	na.	na.	na.	na.	yes	30
4	no/na.	1	1	na.	na.	na.	yes	yes	100
3	no/na.	1	1	yes	yes	na.	yes	yes	30
6	no/na.	1	2	na.	yes	na.	yes	yes	60
3	no/na.	2	2	na.	na.	na.	na.	yes	40
4	no/na.	2	2	na.	yes	na.	na.	yes	60
3	no/na.	1	1	yes	yes	na.	na.	yes	30
3	no/na.	2	2	yes	yes	na.	yes	yes	50
4	no/na.	1	1	na.	yes	na.	yes	yes	30
3	no/na.	2	2	yes	yes	yes	yes	yes	60
3	no/na.	2	2	yes	yes	yes	yes	yes	60
3	no/na.	3	1	na.	yes	na.	na.	yes	110
3	no/na.	2	1	na.	yes	na.	na.	yes	110
3	no/na.	2	1	na.	na.	na.	na.	yes	110
3	yes	3	1	na.	yes	na.	na.	yes	110
3	no/na.	1	1	na.	na.	na.	na.	yes	110
3	no/na.	1	1	na.	yes	na.	na.	yes	110
3	no/na.	1	1	na.	na.	na.	na.	yes	110
3	no/na.	1	1	na.	yes	na.	na.	yes	110
3	yes	3	1	na.	yes	na.	na.	yes	110
3	yes	3	1	na.	yes	na.	na.	yes	110
3	no/na.	2	1	na.	yes	na.	na.	yes	110
3	no/na.	2	1	na.	yes	na.	na.	yes	110
3	no/na.	1	1	na.	yes	na.	na.	yes	110
3	no/na.	2	1	na.	yes	na.	na.	yes	110
3	no/na.	1	1	na.	na.	na.	na.	yes	110
3	no/na.	1	1	na.	yes	na.	na.	yes	110
3	no/na.	2	2	na.	yes	na.	yes	yes	30
3	yes	2	1	yes	yes	na.	yes	yes	60
3	yes	2	1	yes	yes	na.	yes	yes	60
3	yes	2	1	yes	yes	na.	yes	yes	60
3	yes	2	1	yes	yes	na.	yes	yes	60
3	yes	2	1	yes	yes	na.	yes	yes	60
4	no/na.	2	2	na.	yes	na.	na.	yes	60
4	no/na.	1	1	na.	na.	yes	yes	yes	50
4	yes	2	1	na.	na.	yes	yes	yes	50
4	yes	2	1	na.	na.	yes	yes	yes	50
3	no/na.	1	1	na.	yes	na.	yes	yes	60
3	no/na.	2	1	yes	yes	yes	na.	na.	30
3	no/na.	2	1	yes	yes	yes	na.	na.	30
4	no/na.	2	2	yes	yes	yes	na.	na.	30
3	no/na.	1	1	yes	yes	yes	na.	na.	120
4	yes	8	2	na.	yes	na.	yes	yes	90
na.	no/na.	2	1	yes	na.	na.	yes	yes	50
3	yes	2	1	na.	na.	yes	na.	na.	40

3	yes	2	1	na.	na.	yes	na.	na.	40
3	no/na.	1	1	yes	yes	na.	yes	yes	60
3	no/na.	1	1	yes	yes	na.	yes	yes	100
3	no/na.	1	1	yes	yes	na.	yes	yes	100
4	no/na.	1	1	na.	yes	yes	na.	na.	30
na.	yes	4	2	yes	na.	yes	yes	yes	100
4	yes	3	1	na.	na.	na.	na.	yes	100
3	yes	3	1	yes	yes	na.	na.	yes	30
4	yes	4	1	na.	na.	na.	na.	yes	30
4	no/na.	1	1	yes	yes	yes	yes	yes	30
4	no/na.	1	1	yes	yes	yes	yes	yes	30
4	no/na.	1	1	yes	yes	yes	yes	yes	30
3	yes	3	1	na.	yes	na.	na.	yes	100
4	no/na.	2	2	na.	yes	yes	na.	na.	30
4	no/na.	1	2	na.	yes	yes	na.	na.	30
4	yes	2	2	na.	yes	yes	na.	na.	30
3	no/na.	2	1	yes	na.	na.	yes	yes	30
3	yes	2	2	yes	yes	yes	na.	na.	30
4	no/na.	1	1	yes	yes	na.	yes	yes	120
3	no/na.	1	1	yes	yes	na.	yes	yes	30
3	no/na.	3	1	na.	yes	na.	yes	yes	30
5	yes	3	1	na.	yes	na.	yes	yes	30
5	yes	3	1	na.	yes	na.	yes	yes	30
3	no/na.	2	2	na.	yes	na.	na.	yes	60
3	no/na.	2	2	yes	yes	na.	yes	yes	60
4	yes	3	1	na.	yes	na.	yes	yes	60
4	yes	1	1	yes	na.	na.	yes	yes	30
3	no/na.	1	1	na.	na.	na.	na.	yes	40
3	no/na.	1	1	na.	na.	na.	na.	yes	40
3	no/na.	1	1	na.	na.	na.	na.	yes	40
3	no/na.	1	1	na.	na.	na.	na.	yes	40
3	no/na.	1	1	na.	na.	na.	na.	yes	40
3	no/na.	1	1	na.	na.	na.	na.	yes	40
4	no/na.	1	1	yes	yes	yes	na.	na.	30
3	yes	2	2	yes	yes	na.	na.	yes	45
3	no/na.	1	1	yes	yes	na.	na.	yes	60
4	no/na.	2	2	yes	yes	na.	yes	yes	30
4	no/na.	2	2	yes	yes	na.	yes	yes	30
3	yes	3	3	yes	yes	na.	na.	yes	45
3	yes	3	3	yes	yes	na.	na.	yes	45
3	yes	3	3	yes	yes	na.	na.	yes	45
3	yes	2	3	na.	yes	na.	na.	yes	45
3	yes	3	1	na.	yes	na.	yes	yes	30
4	no/na.	1	2	na.	na.	na.	na.	yes	30
4	no/na.	1	2	na.	yes	na.	na.	yes	30
3	no/na.	2	2	yes	yes	na.	yes	yes	60
na.	yes	5	2	yes	na.	na.	yes	yes	100
3	yes	2	2	na.	yes	na.	yes	yes	30
3	yes	2	2	na.	yes	na.	yes	yes	30
3	yes	2	2	na.	yes	na.	yes	yes	30
2	no/na.	1	2	yes	yes	na.	yes	yes	30
2	yes	2	2	yes	yes	na.	yes	yes	30
4	no/na.	1	1	yes	yes	na.	yes	yes	30
4	yes	2	1	yes	yes	na.	yes	yes	30
3	yes	2	1	na.	na.	na.	yes	yes	30
3	yes	2	1	na.	na.	na.	yes	yes	30
3	yes	3	2	na.	yes	na.	na.	yes	30
3	no/na.	2	2	yes	na.	yes	na.	na.	100
3	no/na.	2	2	yes	na.	yes	na.	na.	100
3	yes	4	2	yes	na.	yes	na.	na.	100
3	no/na.	2	2	yes	yes	yes	na.	na.	100
3	no/na.	2	2	yes	yes	yes	na.	na.	100
3	yes	4	2	yes	yes	yes	na.	na.	100

3	yes	3	1	yes	yes	na.	yes	yes	40
4	no/na.	1	1	na.	yes	yes	na.	na.	30
4	yes	4	2	na.	yes	yes	na.	na.	30
4	yes	4	2	na.	yes	yes	na.	na.	30
4	yes	4	2	na.	yes	yes	na.	na.	30
3	yes	2	1	na.	na.	na.	yes	yes	90
3	yes	2	1	na.	na.	na.	yes	yes	90
3	yes	2	1	na.	na.	na.	yes	yes	90
6	yes	6	2	na.	na.	na.	yes	yes	90

Soil profiles which SOC measured	Determined BD equation	Profile SOC Simulated	SOC stock-CT (0-
0-5, 5-10, 10-20, 20-30	no	no	41.9
0-5, 5-10, 10-20, 20-30	no	no	46.1
0-5, 5-10, 10-20, 20-30	no	no	49.0
0-5, 5-10, 10-20, 20-30	no	no	42.2
0-5, 5-10, 10-20, 20-30	no	no	58.4
0-5, 5-10, 10-20, 20-30	no	no	46.8
0-5, 5-10, 10-20, 20-30	no	no	57.5
0-5, 5-10, 10-20, 20-30	no	no	44.1
0-5, 5-10, 10-20, 20-30	no	no	46.4
0-5, 5-10, 10-20, 20-30	no	no	47.9
0-5, 5-10, 10-20, 20-30	no	no	46.3
0-5, 5-10, 10-20, 20-30	no	no	46.4
0-10, 10-20, 20-30, 30-40	no	no	28.5
0-10, 10-20, 20-30, 30-40	no	no	35.9
0-10, 10-20, 20-30, 30-40	no	no	33.0
0-10, 10-20, 20-30, 30-40	no	no	31.8
0-10, 10-20, 20-30, 30-40	no	no	33.1
0-10, 10-20, 20-30, 30-40	no	no	31.2
0-10, 10-20, 20-30, 30-40	no	no	32.1
0-10, 10-20, 20-30, 30-40	no	no	31.7
0-10, 10-20, 20-30, 30-40	no	no	33.4
0-10, 10-20, 20-30, 30-40	no	no	29.5
0-5, 5-10, 10-20, 20-30, 30-40	no	no	51.1
0-5, 5-10, 10-20, 20-30, 30-40	no	no	36.7
0-5, 5-10, 10-20, 20-30, 30-40	no	no	34.9
0-5, 5-10, 10-20, 20-30, 30-40	no	no	32.0
0-3, 3-13,13-26, 26-52	yes	yes	23.9
0-3, 3-13,13-26, 26-52	yes	yes	25.8
0-10, 10-20, 20-30, 30-40	yes	no	49.4
0-10, 10-20, 20-40	yes	yes	66.6
0-10, 10-20, 20-40	yes	yes	73.4
0-5, 5-10, 10-20, 20-30, 30-40, 40-50, 50-60	no	no	104.4
0-5, 5-10, 10-20, 20-30, 30-40, 40-50, 50-60	no	no	109.5
0-5, 5-10, 10-20, 20-30, 30-40, 40-50, 50-60	no	no	59.7
0-5, 5-10, 10-20, 20-30, 30-40, 40-50, 50-60	no	no	75.1
0-15, 15-30	no	no	49.4
0-15, 15-30	no	no	53.9
0-10, 10-20, 20-30	yes	no	67.5
0-10, 10-20, 20-30	yes	no	67.8
0-5, 5-10, 10-20, 20-40, 40-60	yes	yes	68.9
0-10, 10-20, 20-30, 30-50	yes	no	74.3
0-4, 4-10, 10-20, 20-35, 35-50, 50-65	yes	yes	37.2
0-4, 4-10, 10-20, 20-35, 35-50, 50-65	yes	yes	38.4
0-4, 4-10, 10-20, 20-35, 35-50, 50-65	yes	yes	37.6
0-4, 4-10, 10-20, 20-35, 35-50, 50-65	yes	yes	37.8
0-4, 4-10, 10-20, 20-35, 35-50, 50-65	yes	yes	70.7
0-4, 4-10, 10-20, 20-35, 35-50, 50-65	yes	yes	68.8
0-4, 4-10, 10-20, 20-35, 35-50, 50-65	yes	yes	63.3
0-4, 4-10, 10-20, 20-35, 35-50, 50-65	yes	yes	62.7
0-5, 5-12.5, 12.5-20, 20-35, 35-50	no	yes	20.1
0-4, 4-8, 8-12, 12-16, 16-20, 20-30	no	no	44.9
0-5, 5-15, 15-30, 30-55, 55-80, 80-105	no	no	35.4
0-5, 5-15, 15-30, 30-55, 55-80, 80-105	no	no	32.6
0-5, 5-15, 15-30, 30-55, 55-80, 80-105	no	no	30.0
0-5, 5-10, 10-20, 20-30, 30-40, 40-50, 50-70, 70-(	yes	no	56.4
0-15, 15-30	yes	no	31.1
0-15, 15-30	yes	no	31.6
0-5, 5-15, 15-30, 30-45, 45-60, 60-75	yes	no	29.2
0-20, 20-55.8, 55.8-100	yes	yes	41.8
0-10, 10-20, 20-30	yes	no	68.0
0-5, 5-10, 10-20, 20-30, 30-45, 45-60	yes	no	92.2
0-5, 5-10, 10-20, 20-30, 30-45, 45-60	yes	no	95.0

0-5, 5-15, 15-30, 30-50, 50-75, 75-100	yes	no	84.1
0-5, 5-10, 10-20, 20-30	yes	no	30.0
0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-45	yes	no	98.7
0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-45	yes	no	112.0
0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-45	yes	no	101.7
0-5, 5-10, 10-15, 15-20, 20-25, 25-30, 30-45	yes	no	107.8
0-10, 10-20, 20-30, 30-40	yes	no	38.3
0-10, 10-20, 20-30, 30-40	yes	no	40.8
0-10, 10-20, 20-30, 30-40	yes	no	90.3
0-10, 10-20, 20-30, 30-40	yes	no	55.0
0-10, 10-20, 20-30, 30-40	yes	no	44.9
0-10, 10-20, 20-30, 30-40	yes	no	107.9
0-5, 5-10, 10-20, 20-30, 30-40	yes	no	40.1
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	76.8
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	50.1
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	68.7
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	81.5
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	54.5
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	40.8
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	74.5
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	52.8
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	49.2
0-5, 5-15, 15-30	yes	no	55.7
0-7.6, 7.6-15.2, 15.2-30.4, 30.4-60.9, 60.9-91.2	yes	yes	62.7
0-7.6, 7.6-15.2, 15.2-30.4, 30.4-60.9, 60.9-91.2	yes	yes	62.5
0-7.6, 7.6-15.2, 15.2-30.4, 30.4-60.9, 60.9-91.2	yes	yes	65.8
0-7.6, 7.6-15.2, 15.2-30.4, 30.4-60.9, 60.9-91.2	yes	yes	65.0
0-7.6, 7.6-15.2, 15.2-30.4, 30.4-60.9, 60.9-91.2	yes	yes	59.0
0-7.6, 7.6-15.2, 15.2-30.4, 30.4-60.9, 60.9-91.2	yes	yes	63.2
0-2.5, 2.5-7.5, 7.5-15, 15-30	no	no	50.6
0-2.5, 2.5-7.5, 7.5-15, 15-30	no	no	44.1
0-2.5, 2.5-7.5, 7.5-15, 15-30	no	no	47.2
0-10, 10-20, 20-30, 30-40	no	no	48.5
0-10, 10-20, 20-30, 30-40	no	no	49.2
0-10, 10-20, 20-30, 30-40	no	no	49.8
0-10, 10-20, 20-30, 30-40	no	no	47.7
0-5, 5-15, 15-30, 30-50, 50-75, 75-100	yes	no	80.4
0-5, 5-15, 15-30, 30-50, 50-75, 75-100	yes	no	86.0
0-5, 5-10, 10-15, 15-20, 20-30, 30-40, 40-60, 60-	yes	no	86.0
0-7.5, 7.5-15, 15-22.5, 22.5-30, 30-45	no	no	69.9
0-7.5, 7.5-15, 15-22.5, 22.5-30, 30-45	no	no	40.7
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	101.1
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	84.7
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	118.3
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	59.3
0-5, 5-10, 10-30, 30-50, 50-60	yes	no	81.8
0-7.6, 7.6-15.2, 15.2-30.4	yes	yes	65.0
0-7.6, 7.6-15.2, 15.2-30.4	yes	yes	63.6
0-10, 10-20, 20-30	yes	no	28.5
0-2.5, 2.5-5, 5-10, 10-20, 20-40	yes	yes	80.9
0-5, 5-10, 10-20, 20-30	yes	no	68.1
0-5, 5-10, 10-20, 20-30	yes	no	65.3
0-7.5, 7.5-15, 15-30, 30-45	yes	no	73.0
0-5, 5-10, 10-20, 20-30	no	no	58.3
0-5, 5-10, 10-15, 15-20, 20-30, 30-40, 40-55, 55-	yes	no	62.2
0-5, 5-10, 10-15, 15-20, 20-30, 30-40, 40-55, 55-	yes	no	59.3
0-5, 5-10, 10-15, 15-20, 20-30, 30-40, 40-55, 55-	yes	no	60.5
0-2.5, 2.5-5, 5-7.5, 7.5-12.5, 12.5-17.5, 17.5-30	no	no	44.7
0-2.5, 2.5-5, 5-7.5, 7.5-12.5, 12.5-17.5, 17.5-30	no	no	50.2
0-2.5, 2.5-5, 5-7.5, 7.5-12.5, 12.5-17.5, 17.5-30	no	no	37.6
0-2.5, 2.5-5, 5-7.5, 7.5-12.5, 12.5-17.5, 17.5-30	no	no	42.1
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0-2.5, 2.5-5, 5-7.5, 7.5-12.5, 12.5-17.5, 17.5-30	no	no	42.8
0-2.5, 2.5-5, 5-7.5, 7.5-12.5, 12.5-17.5, 17.5-30	no	no	43.8
0-30	yes	no	59.8
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0-2.5, 2.5-5, 5-10, 10-20, 20-40	no	yes	91.0
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0-30	no	no	49.9
0-30	no	no	50.9
0-30	no	no	45.2
0-30	no	no	45.4
0-30	no	no	45.4
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0-30	no	no	18.8
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0-5, 5-15, 15-30, 30-50, 50-75, 75-100	yes	no	40.2
0-15, 15-30	yes	no	37.1
0-10, 10-20, 20-30, 30-60	yes	no	27.8
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0-5, 5-10, 10-20, 20-30	no	no	28.8
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0-5, 5-10, 10-20, 20-30	yes	no	64.4
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0-2.5, 2.5-5, 5-10, 10-20, 20-40, 40-60	yes	yes	30.4
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0-10, 10-20, 20-40, 40-70, 70-110	no	yes	39.3
0-10, 10-20, 20-40, 40-70, 70-110	no	yes	39.2
0-10, 10-20, 20-40, 40-70, 70-110	no	yes	37.1
0-10, 10-20, 20-40, 40-70, 70-110	no	yes	41.3
0-10, 10-20, 20-40, 40-70, 70-110	no	yes	39.1
0-10, 10-20, 20-40, 40-70, 70-110	no	yes	39.0
0-10, 10-20, 20-40, 40-70, 70-110	no	yes	40.9
0-10, 10-20, 20-40, 40-70, 70-110	no	yes	37.2
0-10, 10-20, 20-40, 40-70, 70-110	no	yes	36.1
0-10, 10-20, 20-40, 40-70, 70-110	no	yes	28.1
0-10, 10-20, 20-40, 40-70, 70-110	no	yes	39.9
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0-5, 5-10, 10-20, 20-30, 30-40, 40-50	yes	no	72.8
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0-5, 5-10, 10-20, 20-30	no	no	33.0
0-5, 5-15, 15-30	no	no	31.7
0-30, 30-60, 60-90, 90-120	no	no	47.2
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0-5, 5-10, 10-20, 20-40, 40-60, 60-80, 80-100	yes	yes	41.1
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0-20, 20-40, 40-60, 60-80, 80-100	yes	yes	94.5
0-25, 25-50, 50-75, 75-100	no	yes	110.7
0-15, 15-30	no	no	36.7
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0-30	yes	no	45.1
0-30	yes	no	46.5
0-30	no	no	47.7
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0-30	no	no	73.5
0-10, 10-30	no	no	55.9
0-30	no	no	51.1
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0-30	no	no	23.3
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0-5, 5-10, 10-20, 20-30	yes	no	30.6
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0-15, 15-30, 30-45, 45-60	no	no	13.7
0-5, 5-10, 10-20, 20-40, 40-60	yes	yes	30.1
0-20, 20-40, 40-60	yes	yes	58.8
0-5, 5-10, 10-20, 20-30	yes	no	31.7
0-5, 5-20, 20-40	no	yes	48.7
0-5, 5-20, 20-40	no	yes	44.9
0-5, 5-20, 20-40	no	yes	43.2
0-5, 5-20, 20-40	no	yes	39.2
0-5, 5-20, 20-40	no	yes	61.7
0-5, 5-20, 20-40	no	yes	46.1
0-30	no	no	33.7
0-5, 5-15, 15-30, 30-45	no	no	21.4
0-5, 5-10, 10-20, 20-30, 30-40, 40-50, 50-60	yes	no	66.3
0-15, 15-30	yes	no	15.9
0-15, 15-30	yes	no	19.2
0-15, 15-30, 30-45	no	no	21.3
0-15, 15-30, 30-45	no	no	22.3
0-15, 15-30, 30-45	no	no	19.6
0-15, 15-30, 30-45	no	no	20.0
0-7.5, 7.5-15, 15-30	no	no	27.5
0-10, 10-20, 20-30	no	no	72.6
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0-20, 20-40, 40-60, 60-80, 80-100	yes	yes	94.5
0-5, 5-10, 10-20, 20-30	yes	no	32.3
0-5, 5-10, 10-20, 20-30	yes	no	28.3
0-5, 5-10, 10-20, 20-30	yes	no	26.7
0-15, 15-30	yes	no	41.1
0-15, 15-30	yes	no	42.6
0-5, 5-10, 10-20, 20-30	yes	no	66.2
0-5, 5-10, 10-20, 20-30	yes	no	68.1
0-10, 10-20, 20-30	yes	no	55.2
0-10, 10-20, 20-30	yes	no	43.6
0-7.5, 7.5-15, 15-30	no	no	21.7
0-30, 30-100	no	no	47.9
0-30, 30-100	no	no	53.8
0-30, 30-100	no	no	56.7
0-30, 30-100	no	no	51.7
0-30, 30-100	no	no	54.4
0-30, 30-100	no	no	55.8

0-5, 5-10, 10-20, 20-30, 30-40	yes	no	74.3
0-30	no	no	46.1
0-30	no	no	45.2
0-30	no	no	43.7
0-30	no	no	43.1
0-15, 15-30, 30-60, 60-90	yes	no	74.4
0-15, 15-30, 30-60, 60-90	yes	no	79.0
0-15, 15-30, 30-60, 60-90	yes	no	92.0
0-15, 15-30, 30-60, 60-90	yes	no	55.1

SOC stock-NT (0-
46.5
53.9
58.3
56.3
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31.5
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40.6
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39.2
38.8
36.8
34.9
46.6
41.1
39.5
34.5
24.1
30.8
53.0
75.6
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73.4
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67.9
66.6
64.5
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42.9
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35.9
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43.4
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92.7
94.6

92.5
22.9
95.1
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72.6
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46.1
50.0
51.8
50.8
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48.0
97.3
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43.2

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58.1
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45.2
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38.9
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Table S2. Sites and numbers of paired data reported SOC under conservation and conventional agriculture included in this study.

Country	Site	n
Australia	7	8
Brazil	11	31
Canada	8	16
China	14	19
Czech	1	2
Denmark	1	1
Ethiopia	1	1
India	6	12
Italy	1	2
Mexico	1	6
Morocco	1	3
Norway	1	1
Russia	1	2
Spain	11	37
Switzerland	1	1
Tanzania	1	1
Tunisia	1	2
USA	66	110
UK	1	1
Uruguay	1	1
Zimbabwe	2	3
Total	138	260

Table S3. Number of paired data used for interpreting impact of conservation agriculture on SOC in this study.

Criterion	Number of paired data
Legume crop	141
Crop yield	53
C input (residue)	94
N input	199
SOC stock (Mg/ha)	75
SOC(SOM) content (g/kg)	217
Determined BD equation	615
Bulk density estimated	68
Profile SOC Simulated	59

Table S4. Estimates of parameter a2 in Eqn. 3 for conventional and conservation farming.

Parameter a2	Estimate	SE	Bootstrap 95% C.I.		n	R^2
			Lower	Upper		
CT	1.547	0.009	1.528	1.566	615	0.225
NT	1.591	0.009	1.574	1.607	615	0.235

Table S5. Variables used in the CRT analysis.

Variables	Unit	Description	n	Mean	Min	Max	SD
T	ºC	Mean annual temperature	260	13.7	-0.9	26.0	5.6
P	mm	Mean annual precipitation	260	795.1	334.0	1746.0	343.1
HI	mm $ºC^{-1}$	Ratio of precipitation to temperature	260	61.9	-422.2	174.6	53.7
Clay	%	Clay content	260	26.9	6.0	62.0	13.2
CS	%	Clay and silt content	260	65.7	14.0	97.0	16.7
Sand	%	Sand content	260	34.3	3.0	86.0	16.7
pH	None	pH (H_2O)	260	6.6	4.5	9.1	1.1
Yr	Year	Experimental duration	260	14.2	5.0	53.0	9.3
Legume	None	Rotation with legume crops (0 = no, 1 = yes)	260	0.5	0	1	0.5
Ncrop	None	Numbers of crops in rotation	260	2	1	8.00	1
Acrop	None	Numbers of crops per year	260	1.3	1.0	3.0	0.5
Ninput	kgN yr^{-1}	Annual fertilizer N input	203	97.8	0.0	550.0	92.9
ΔYield	MgC ha^{-1} yr^{-1}	Difference of annual crop yield between two farming systems	53	0.08	-1.32	2.67	0.67
ΔCinput	MgC ha^{-1} yr^{-1}	Difference of annual C input between two farming systems	94	0.2	-0.4	3.9	0.6
$ΔSOC_R$	MgC ha^{-1} yr^{-1}	Difference of SOC two farming systems per year	260	0.4	-2.8	4.0	0.8

Table S6. Description of datasets of SOC (Table S1, n=260) and crop yield (Pittelkow et al., 2015a and this study, Table S1) with no-till combined either residue retained or crop rotation (incl. cover crop) (n=1444). HI is humidity index defined as annual mean precipitation to annual mean temperature ratio, MAP/MAT.

	HI <40	40≤ HI <60	60≤ HI <80	80≤ HI ≤100	HI >100	Mean
SOC dataset						
n	79	51	43	52	35	
HI	19.8 (31.3)*	49.2	70.7	89.5	124.0	61.9
SE	8.1	0.8	0.8	0.9	3.4	3.3
ΔSOC_R (MgC ha^{-1} yr^{-1})	0.47	0.36	0.40	0.22	0.18	0.35
SE	0.07	0.07	0.10	0.15	0.17	0.05
Crop yield dataset‡						
n	260	305	291	336	252	
HI	30.4	49.4	71.1	91.5	160.7	79.5
SE	0.5	0.3	0.2	0.2	3.5	1.3
ΔYield (Mg ha^{-1})	0.03	-0.13	0.00	-0.32	-0.51	-0.18
SE	0.05	0.05	0.05	0.05	0.08	0.03

* The number showed in parenthesis is mean of HI excluding 2 cases which have a negative HI (Table S1 and S5).

‡ Data source is the same as 'RR+CR' plus 'RR/CR' in Figure 4.

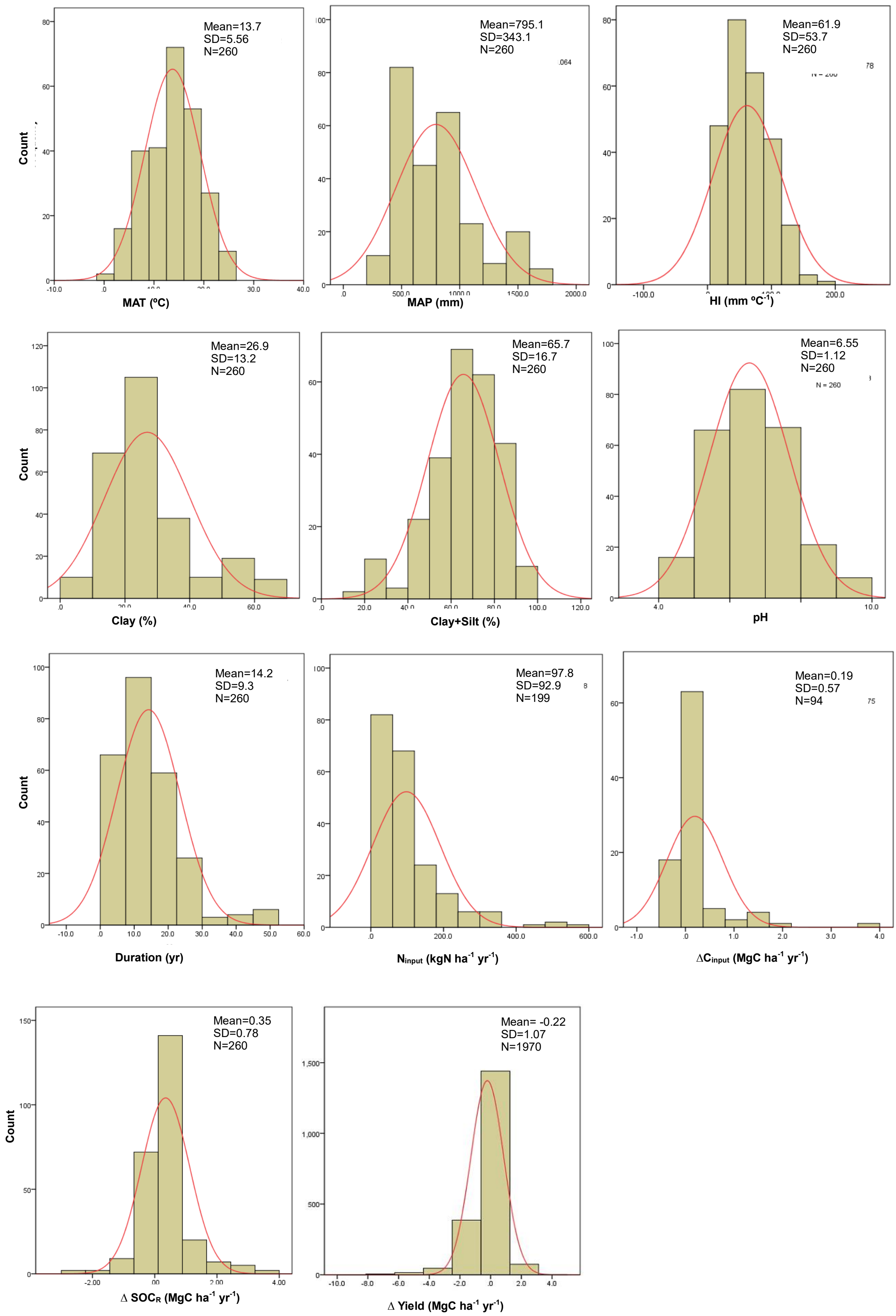

Figure S1. Count distribution of variables in this study.

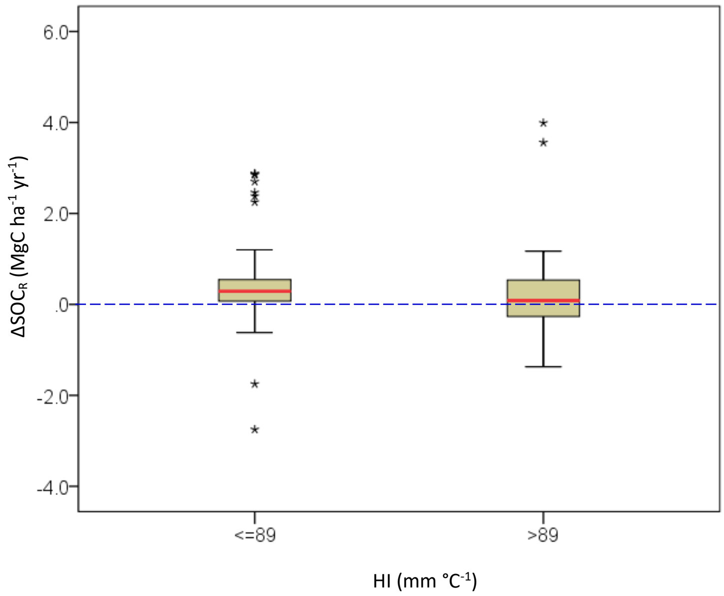

Figure S2. Annual change of SOC stock (ΔSOC_R) under different humidity index through conversion to conservation farming.

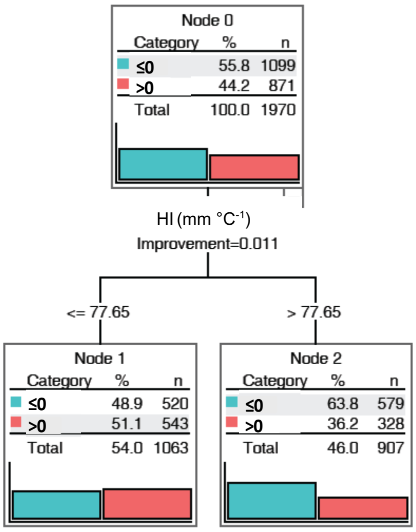

Figure S3. CRT predicting gain or loss of crop yield due to no-till adoption. Crop yield date (n=1970) are from Table S1 (n=53) and Pitteklow et al., 2015 (n=1917)