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Agricultural management impacts on soil organic carbon storage under moist and dry climatic conditions of temperate and tropical regions

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Abstract. We conducted a meta-analysis to quantify the impact of changing agricultural land use and management on soil organic carbon (SOC) storage under moist and dry climatic conditions of temperate and tropical regions. We derived estimates of management impacts for a carbon accounting approach developed by the Intergovernmental Panel on Climate Change, addressing the impact of long-term cultivation, setting-aside land from crop production, changing tillage management, and modifying C input to the soil by varying cropping practices. We found 126 articles that met our criteria and analyzed the data in linear mixed-effect models. In general, management impacts were sensitive to climate in the following order from largest to smallest changes in SOC: tropical moist > tropical dry > temperate moist > temperate dry. For example, long-term cultivation caused the greatest loss of SOC in tropical moist climates, with cultivated soils having 0.58 ± 0.12, or 58% of the amount found under native vegetation, followed by tropical dry climates with 0.69 ± 0.13, temperate moist with 0.71 ± 0.04, and temperate dry with 0.82 ± 0.04. Similarly, converting from conventional tillage to no-till increased SOC storage over 20 years by a factor of 1.23 ± 0.05 in tropical moist climates, which is a 23% increase in SOC, while the corresponding change in tropical dry climates was 1.17 ± 0.05, temperate moist was 1.16 ± 0.02, and temperate dry was 1.10 ± 0.03. These results demonstrate that agricultural management impacts on SOC storage will vary depending on climatic conditions that influence the plant and soil processes driving soil organic matter dynamics.

Introduction

Land use and management of agricultural systems is known to change the storage of soil organic carbon (SOC) through variation in land use, tillage, cropping practices (intensity and types of crops), irrigation, fertilization, and other activities (Paustian et al. 1997a; Bruce et al. 1999). Consequently, management and land use can be used to mitigate greenhouse gas emissions by encouraging practices that sequester carbon (C) in the soil, thus creating a C sink for atmospheric CO_2 (Kern and Johnson 1993; Paustian et al. 1997a, b; Lal et al. 1998; Buyanovsky and Wagner 1998; Paustian et al. 2000; Smith et al. 2000; Kucharik et al. 2001; Follett 2001; Wu et al. 2003). Moreover, policymakers have included the usage of C sinks for mitigation purposes in international negotiations, set forth in the Kyoto Protocol (Article 3.3 and 3.4, UNFCCC 1997) and Marrakech Accords.

While it is well known that these practices impact SOC storage, quantitative estimates vary across studies for a variety of reasons, including climatic constraints on the processes that influence soil organic matter dynamics. However, there have been few analyses synthesizing data at the regional to global scale that evaluate the underlying reasons for this apparent variability. One example is a study conducted by West and Post (2002) that addressed the effects of crop types on carbon sequestration with adoption of no-till management. However, there study did not explicitly consider how the management change would alter sequestration rates in different climates. Results from such analyses could ultimately be used to estimate management impacts on SOC storage in national inventories, which will be needed for countries to report carbon sequestration under international treaty agreements.

The Intergovernmental Panel on Climate Change (IPCC) has developed an approach for conducting these inventories, but the method lacks rigorous statistical estimates of management impacts (IPCC 1997). Therefore, our objective was to provide empirically derived estimates for the IPCC method by analyzing results from a global data set of experiments addressing the change on SOC storage for a variety of agricultural activities (IPCC 2004). Through this analysis, we evaluated the variation in responses under moist and dry climatic conditions of temperate and tropical regions.

Agricultural management is initiated with the conversion of native ecosystems (e.g., grasslands and forests) into cropland. Plowing native lands leads to dramatic losses of SOC (Mann 1986; Davidson and Ackerman 1993; Murty et al. 2002) through intensive soil disturbance that disrupts soil structure and enhances decomposition (Elliott 1986; Six et al. 2002), in addition to accelerating soil erosion (Pimental et al. 1976). Cultivation also redistributes organic C deeper in the profile through the mixing action of tillage implements (Follett and Peterson 1988).

Even though plowing has a rather pervasive impact, land managers can vary their tillage intensity, and change the amount of SOC that is stored in cropland soils. The most intensive practices invert and thoroughly mix the soil (e.g., moldboard plow), which leads to high decomposition and erosion rates (Reicosky and Lindstrom 1993; Reicosky et al. 1995; Doran et al. 1998). In contrast, less intensive practices, particularly no-till, reduce soil erosion through the development of a litter layer (Karlen et al. 1994), and also enhance aggregate stability in the soil that slows decomposition of organic matter by providing protection within soil aggregates (Elliott 1986; Jastrow 1996; Six et al. 1998, 2000). Consequently, reducing tillage intensity typically increases storage of SOC relative to conventional till practices (e.g., Mielke et al. 1986; Lal et al. 1994; Franzluebbers et al. 1995; Dick et al. 1997; Larney et al. 1997; Salinas-Garcia et al. 1997; Doran et al. 1998; Barber et al. 1996; Sa et al. 2001; Bayer et al. 2002).

Productivity of individual crops influences SOC storage due to differences in the amount of crop residue that is left in the agricultural field and incorporated into soil organic matter. For example, Eghball et al. (1994) demonstrated higher residue production in continuous corn than corn–soybean (*Zea Mays* L.–*Glycine max* (L.)Merr.) rotations, leading to greater SOC storage. Similarly, winter cover crops or including a year(s) of hay, or pasture in crop rotations can increase overall production and C input to the soil (Janzen 1987; Bremer et al. 1994). Other crops, such as cotton (*Gossypium hirsutum* L.), produce relatively small amounts of residue, leading to low C input to the soil (Bordovsky et al. 1999).

Cropping intensity, or frequency, also affects SOC storage by modifying the amount of time that the soil is supporting a crop, and therefore can increase annual production and C input to the soil. In addition, intensification can reduce decomposition rates that are often high if fields are bare of vegetation, such as with 'summer-fallowing' to increase soil moisture in croplands that occur in semi-arid regions (Paustian et al. 2000). Increasing cropping frequency is typically done by limiting or suspending the use of bare summer-fallow or through the use of cover crops, and both practices have been shown to increase SOC storage in field experiments (e.g., Bremer et al. 1994; Larney et al. 1997; Potter et al. 1997; Frye and Blevins 1997; Black and Tanaka 1997; Halvorson et al. 2002; Sainju et al. 2002; Sherrod et al. in press).

Similar to rotation impacts, organic amendments and irrigation can increase SOC storage by enhancing plant production and subsequent C input to the soil (e.g., Campbell and Zentner 1993; Gregorich et al. 1996; Salinas-Garcia et al. 1997; Buyanovsky and Wagner 1998; Bordovsky et al. 1999; Clapp et al. 2000; Grandy et al. 2002). Moreover, organic manures directly add C to the soil pool as they decompose (Bremer et al. 1994).

Sometimes land managers restore cultivated fields to perennial vegetation, such as grasslands and forest, which also impacts SOC storage (Paustian et al. 1997a). For example, the Conservation Reserve Program (CRP) has led to the removal of highly erodible lands from crop production in the U.S., by planting grasses or trees, and numerous studies have shown that SOC content increases in these set-aside lands (Gebhart et al. 1994; Potter et al. 1999; Follett et al. 2001; Unger 2001).

The effect of land use and management practices largely determine the net C balance of agricultural soils, and here we provide statistically based estimates of those impacts for several activities, including (1) long-term cultivation, (2) changing tillage management, (3) modifying C input to the soil by varying cropping practices, and (4) setting-aside land from crop production. Through this synthesis, we evaluate the potential for soils to serve as a C sink for atmospheric CO_2 through land use and management change in temperate and tropical agricultural systems, under moist and dry climate regimes.

Methods

IPCC carbon accounting method

As stated in the objective, this research was conducted to provide empirical estimates for the IPCC method, and here we briefly describe that approach to provide the context in which this analysis was conducted. The method is a partial accounting application using a bottom-up approach for estimating change in SOC storage due to land use and management (IPCC 1997). It is a relatively simple accounting method that can be applied in any region, even if there are few resources or information to conduct an inventory. It has been used to estimate impacts on SOC storage in the US (Eve et al. 2002, Ogle et al. 2003), and may be used to estimate emission offsets for compliance under international treaties.

The method was developed to compute the change in SOC storage from a baseline condition using management factors, which are numerical values representing the relative change in SOC storage due to land use and management activities. Change in SOC storage is computed using the equation:

$$\delta C = \sum_{h=1}^{H} (\mathrm{SOC}_t(h) - \mathrm{SOC}_{t-20}(h)), \tag{1}$$

where H is the number of climate regions by soil types by land use/management systems, SOC_t is the stock in the last year of the inventory, and SOC_{t-20} is the stock in the first year. The differences in SOC are summed across all land use and management systems (h). SOC stocks are computed using the equation:

$$\mathrm{SOC}(h) = \mathrm{RC} * \mathrm{BF} * \mathrm{TF} * \mathrm{IF} * \mathrm{LA}, \tag{2}$$

where RC is the reference C stock, BF is the base factor (relative C storage compared to the native system), TF is the tillage factor, IF is the input factor, and LA is the land area for a particular land use and management system (h).

Figure 1 is a conceptual diagram showing the effects of agricultural management on SOC storage as represented in the IPCC method. Reference C stocks (RC) are the amount of SOC stored under native conditions, and base factors (BF) are used to compute the relative change in storage from the reference native condition following long-term cultivation (i.e., the factor represents the change in SOC storage for land that has been cultivated for at least 20 years). Additional factors are used to modify the SOC storage under long-term cultivation. Tillage factors (TF) represent the relative difference in storage between conventionally tilled cropland compared to no-till and reduced till systems. No-till systems are not plowed, which maintains a litter layer on the soil surface, while reduced till systems, such as those managed with chisel, mulch or ridge plowing, typically have 60% of the ground cov-

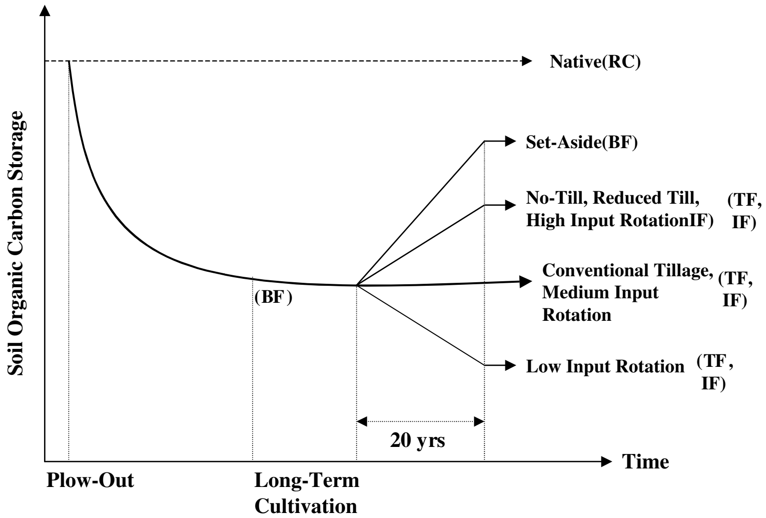

Figure 1. Conceptual framework for the IPCC method. Long-term cultivation causes substantial losses of SOC from the amounts found under native vegetation. Changing tillage, cropping system or set-aside land from crop production are management activities that can alter the long-term loss of soil organic carbon in agricultural lands.

ered with residue. In contrast, conventional tillage (e.g., moldboard plow) inverts the soil during plowing, leaving less than 30% residue cover. Input factors (IF) are used to estimate the relative effect of increasing or decreasing C input to the soil. This occurs through enhancement or reduction of crop productivity compared to medium input cropping systems, which are defined as continuous cereal or row crop rotations with residues returned to the field after harvest. Low input systems have reduced C inputs relative to medium input, due to the inclusion of bare fallow or rest years in a rotation, planting low residue crops such as vegetables, or due to burning or removal of residues. High input systems have increased C input through the use of winter cover crops, green manures, irrigation, high residue crop varieties, or rotations that have a year(s) of hay or pasture. Organic amendments also affect SOC storage by increasing C input to the soil and stimulating production. In the IPCC classification, low input cropping systems are given a medium input status if amended, which is a trade-off between the low residue crop practice and the enhanced C input. Similarly, medium input cropping systems are reclassified as high input if they are amended. High input systems that receive organic amendments are given a special status, referred to as high input with amendment, due to the relatively large inputs compared to the other cropping systems. Lastly, the effect of setting-aside land from production is estimated from a base factor (BF) representing the gain in SOC storage after 20 years, relative to the amount of carbon stored under native conditions. Set-aside lands are generally placed in a reserve status for short time spans, and thus are not expected to regain the full amount of SOC found under native conditions.

Literature search and statistical analysis

We conducted a literature search to find articles from temperate and tropical regions assessing management impacts using several criteria. First, we selected studies that either provided SOC stocks or the information necessary to calculate SOC stocks. By only using these studies, we avoided the uncertainty of attempting to derive SOC stocks by approximating the necessary information (i.e., some studies provide percentage C data but not bulk density). Second, studies needed to report the depth of measurement and time frame over which the management change had occurred. This enabled us to estimate management impacts at specific time frames and depths, in accordance with the IPCC method. Third, studies had to provide the location or climate data for the study sites so that we could classify them into climate regimes. The IPCC (1997) method provided guidelines for this classification, in which sites were classified as tropical if the mean annual temperatures were ≥20 °C and temperate if the mean annual temperatures were <20 °C. Sites in tropical regions were considered to have moist (or wet) climates if the mean annual precipitation was ≥ 1000 mm, while they were considered dry if the mean annual precipitation was <1000 mm. The moisture threshold in temperate regions was based on the precipitation/PET ratio, in which sites with ratios ≥ 1 were considered moist, and those with ratios <1 were considered dry.

We estimated management factors by fitting the published data in linear mixed-effect models, which are an extension of the commonly used regression techniques in natural sciences to include both the fixed and random effects (Pinheiro and Bates 2000). The response variable was the ratio of the SOC stock for the management change to the SOC stock in the baseline condition. This metric is called the response ratio, and it is equivalent to the factor values used in the IPCC method (IPCC 1997). We did not attempt to do a weighted meta-analysis using this response because the majority of the studies did not report variances for the individual treatments.

In some of the set-aside studies, the baseline condition was cultivated cropland instead of a native reference that is used by the IPCC method for estimating the impact of setting-aside land from production. For those studies, we approximated the native stock for the response ratios (set-aside stock/native stock) by dividing the measured stock for long-term cultivated control in the respective study by the estimated factor for the effect of long-term cultivation based on our statistical analysis. This approximation allowed us to include several additional studies, and although not optimal was deemed a necessity given the small number of experiments evaluating this management impact.

Fixed effects were assumed for climate, depth and time after the management change, and we included all first-order interaction terms that were significant among the fixed effects at an alpha level of 0.05. Our treatment of depth in the regression analysis is somewhat unique. Each study included one or more depth increments, such as 0–5, 5–10 and 10–20 cm, and often the upper (U) and lower positions (L) for depth increments did not match across studies. In order to avoid the loss of information through aggregation of data to a standard set of depths using an interpolation technique, regressors were formed from the U and L values of each increment by assuming that the SOC stock ratio declined as a quadratic function of depth, such that

$$\mathrm{B_o} + \mathrm{B_1}D + \mathrm{B_2}D^2 \tag{3}$$

where D represents a specific depth, such as 15 cm. A quadratic function was chosen based on the assumption that agricultural management impacts would be greatest at the surface and diminish with depth in the soil profile. Note that the data do not provide direct observations of SOC stocks at specific depths, such as 15 cm, but rather stocks across increments such as 10–20 cm. Therefore, the average SOC stock ratio for a single increment was the integral from U to L depth positions of the quadratic function divided by thickness of the increment. The integration results in two regression variables for each depth increment

$$X_1 = (L^2 - U^2)/(2 * (L - U)) \tag{4}$$

$$X_2 = (L^3 - U^3)/(3 * (L - U)) \tag{5}$$

that is,

$$\int_U^L \frac{(\mathrm{B_o} + \mathrm{B_1}D + \mathrm{B_2}D^2)}{L - U} \mathrm{d}t = \beta_0 + \beta_1 X_1 + \beta_2 X_2. \tag{6}$$

This approach allowed us to capture the changing relationship across depth between management treatments and SOC storage, without an aggregation of data and loss of information.

Random effects were included in the model for study and a study-by-time interaction in order to account for dependence among measurements within the same study (i.e., commonly used linear regression models in natural sciences, which only have fixed effects, assume that each observation is independent). The random effect for study is a latent random variable common to all observations from the same study (for different depth increments and sampling times), but independent across distinct studies. This random effect captured the dependence, or more specifically correlations, among measurements from the same study. Similarly, the study-by-time interaction is a latent random variable common to all observations in a given year for a particular study (different depth increments), accounting for the dependence among measurements taken in the same experiment at a specific sampling time. This random-effects formulation is a standard model for repeated measures (e.g., Pinheiro and Bates 2000).

We estimated management factor values from the statistical models based on the integrated impact in top 30 cm of the soil profile (using X_1 and X_2, Eqs. 4 and 5) for the first 20 years following a management change, and then computed standard errors for the factor value estimates. These standard errors reflect the uncertainty in the management factors and can be used to approximate probability distribution functions for a national inventory analysis (Ogle et al. 2003). We conducted all statistical analyses using SPLUS 2000 Professional software, release 3 (Insightful Corporation, Seattle, Washington).

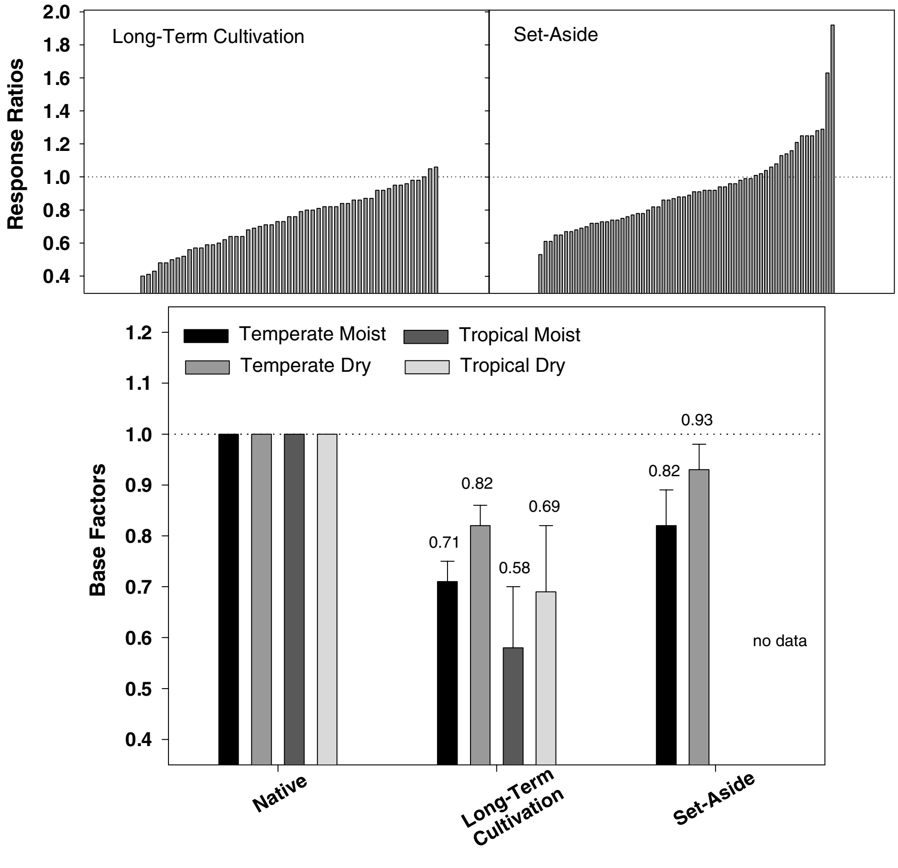

Figure 2. Response ratios (ratio of soil organic carbon content in cultivated treatment relative to uncultivated) from individual studies and statistically derived factor estimates (±1SE) (integrated effect of management over the top 30 cm of the soil profile) for the change in SOC storage due to long-term cultivation (> 20 years) and setting-aside land from crop production (< 20 years).

Results

We found 126 articles meeting the criteria for the analysis (Appendix 1). Of those, 80 articles dealt with tillage, 31 dealt with cropping rotations and intensity (i.e., input), 30 dealt with long-term cultivation, and 17 dealt with lands set-aside from agricultural production. Some of these studies reported data for multiple sites or management practices, and one unpublished study was included in the analysis (Paustian and Elliott, unpublished data).

Long-term cultivation reduced SOC storage in almost every study based on the response ratios (Figure 2). At a couple of arid land sites, SOC storage remained near levels found under native vegetation. Apparently these soils lost little C with long-term cultivation, but there was a redistribution of C deeper in the profile with plowing (Reeder et al. 1998). Integrated over the top 30 cm of the soil profile, tropical moist climates lose the largest amount of SOC with long-term cultivation, where C stocks declined to 0.58 ± 0.12, or 58% of the amount found under native vegetation, followed by tropical dry climates at 0.69 ± 0.13, temperate moist at 0.71 ± 0.04, and temperate dry at 0.82 ± 0.04 of the amount found under native vegetation. These trends were relatively consistent with other syntheses that estimate losses of SOC due to long-term cultivation at 20–30%, which would represent factors of 0.80–0.70 (Mann 1986; Davidson and Ackerman 1993; Murty et al. 2002).

Tillage management had a more variable impact on SOC storage than long-term cultivation in terms of both increases and decreases in storage with the implementation of reduced and no-till practices according to the field experiments (Figure 3). More than half of the response ratios were positive for both reduced and no-till systems, demonstrating that these practices most often increase SOC storage, but there were studies that found no increase in storage relative to conventional tillage (e.g., Dalal 1991; Angers et al. 1997; Black and Tanaka 1997; Wander et al. 1998; Taboada et al. 1998; Duiker and Lal 1999; Franzleubbers et al. 1999; Wanniarachchi et al. 1999; Halvorson et al. 2002). Integrated over the top 30 cm of the soil profile, reduced tillage (e.g., ridge, mulch or chisel plowing) had very little if any impact on SOC in the temperate dry climates, with storage increasing by a factor of 1.03 ± 0.03 during the first 20 years after a management change, which is only an average increase of 3%. Moreover, even the uncertainty in a modest 80% confidence interval (0.99–1.07) will include a factor value of 1, which would represent no change in carbon storage (Eq. 2). There were more substantial impacts in the other climate regions, however, estimated at factors of 1.09 ± 0.03 in temperate moist climates, 1.10 ± 0.05 in tropical dry climates, and 1.16 ± 0.02 in tropical moist climates. Compared to reduced tillage practices, changing from conventional tillage to no-till increased SOC by even larger amounts across each of the climatic regions, ranging from a factor of 1.10 ± 0.03 in temperate dry climates to 1.16 ± 0.02 in temperate moist climates, 1.17 ± 0.05 in tropical dry climates, and 1.23 ± 0.05 in tropical moist climates.

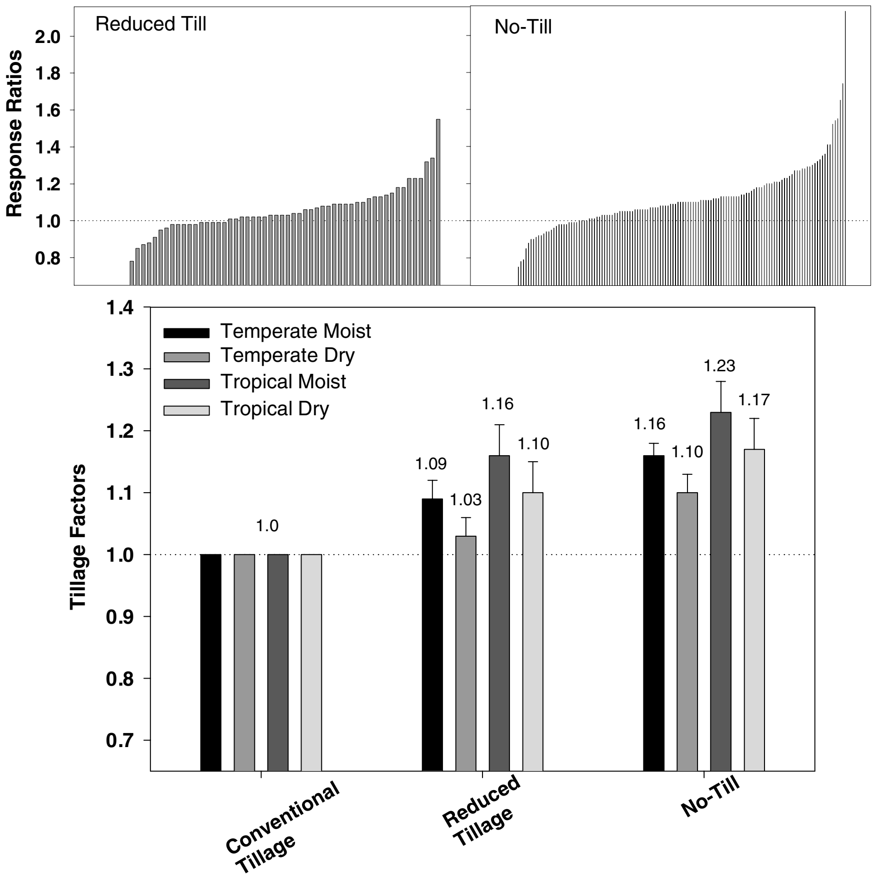

Figure 3. Response ratios (ratio of soil organic carbon content in reduced or no-till treatment relative to conventional tillage) from individual studies and statistically derived factor estimates (±1SE) (integrated effect of management over the top 30 cm of the soil profile) for the change in SOC storage due to changing from a conventional tillage practice to reduced or no-till management (after 20 years).

Variation in rotation practice and the use of organic amendments or irrigation affected SOC storage (Figure 4), but the impacts were mostly smaller than those estimated for tillage. Also, there were not enough studies to assess differences between tropical and temperate regions ($<$ 10 from tropics). If residues were removed from the field or the rotations produced little residue, such as vegetables, tobacco and cotton, response ratios showed that SOC storage declined in most studies relative to the amount found in medium input rotations. Integrated over the top 30 cm, low input rotations were estimated to decrease storage after 20 years to 0.91 ± 0.04 and 0.92 ± 0.02, or 91–92% of

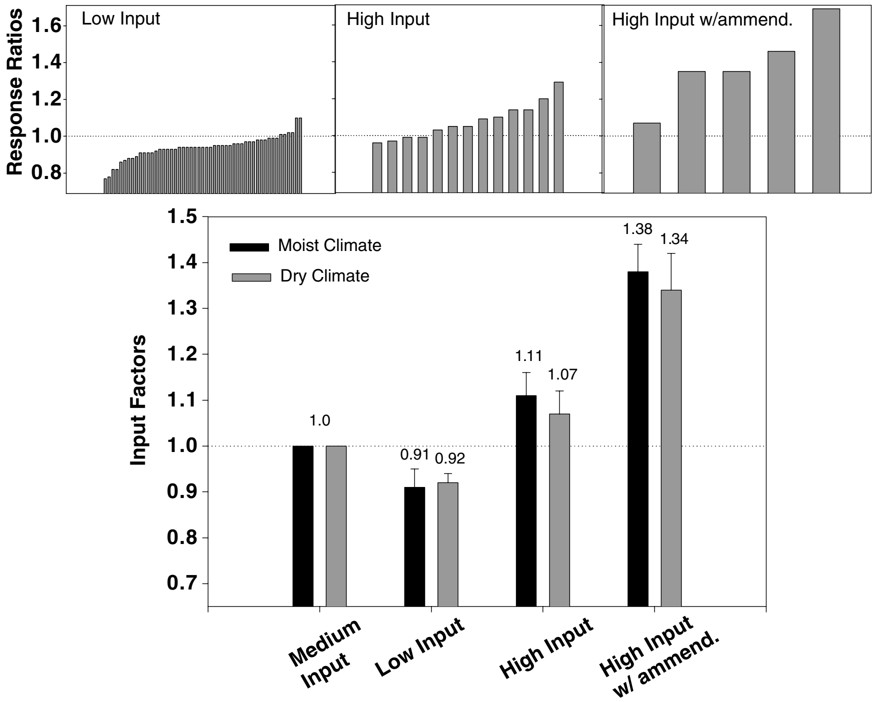

Figure 4. Response ratios (ratio of soil organic carbon content in low or high input treatment relative to medium input) from individual studies and statistically derived factor estimates ($\pm$1SE) (integrated effect of management over the top 30 cm of the soil profile) for the change in SOC storage due to changing the cropping practices from a medium to a low or high carbon input system (after 20 years).

the amount of SOC under medium input rotations in moist and dry climates, respectively. Enhancing residue production by planting more productive varieties or using winter cover crops, increased SOC storage relative to the medium input rotations for the majority of studies based on response ratios. The integrated impact of these enhancements over the top 30 cm of the soil profile was estimated at a factor of 1.07 $\pm$ 0.05 and 1.11 $\pm$ 0.05 for dry and moist climates, respectively, representing a 7–11% increase after 20 years. Although few studies were found addressing the impact of amending high input rotations with organic residues, each study consistently showed increases in SOC storage according to response ratios. After 20 years, high input rotations with amendments were estimated to increase storage in the top 30 cm of the soil profile by a factor of 1.34 $\pm$ 0.08 and 1.38 $\pm$ 0.06 in dry and moist climates, respectively.

Setting-aside land also increased SOC levels above the amounts found under long-term cultivation (Figure 2), with the exception of a few experiments that showed no gain (Baer et al. 2000, Bowman and Anderson 2002). Surprisingly, some studies found that there was more SOC stored in the set-aside land than under native vegetation (Chan and Mead 1988; Follett et al. 2001; Unger 2001). Integrated over the top 30 cm, setting-aside land for 20 years was estimated to restore SOC levels within 0.82 ± 0.07 and 0.93 ± 0.05, or 82–93% of native stock levels in temperate moist and dry climates, respectively. We did not find enough studies to evaluate the impact of setting-aside land in tropical regions.

Discussion

Long-term cultivation reduced SOC storage, but losses varied depending on the climate in the order of tropical moist > tropical dry > temperate moist > temperate dry. Changing tillage and cropping practices also altered SOC storage, and the trends in temperate versus tropical regions were similar to the patterns for long-term cultivation. For example, implementation of no-till or reduced tillage led to the largest increases in SOC storage under tropical moist conditions and the smallest increases under temperate dry conditions. Similarly, high input cropping systems, even those with organic amendments, gained more SOC under moist climates compared to dry climates. While we are not able to determine the underlying mechanistic reasons for these climatic patterns based on this analysis, the biochemical kinetics of the processes involved with (1) breakdown of SOM following cultivation, (2) formation of aggregates in soils after a change in tillage, and (3) increased productivity and C input with the implementation of a new cropping practice, are likely to occur at a more favorable rate under the temperature regimes of tropical regions and in more moist climatic conditions. In turn, this leads to a larger change in SOC storage.

The one exception to this general pattern in climatic constraints on management impacts was the use of low input rotations, which showed basically the same loss of SOC over 20 years in moist and dry climates. This result suggests that reducing input through residue removal, fallowing or planting low residue crops, has an overriding effect on C inputs and SOC storage regardless of the climate and its influence on the biochemical kinetics of these systems.

The impacts of agricultural management according to the meta-analysis results were consistent with the general patterns represented in Figure 1, which were based on the conceptual framework developed by the IPCC working group on agricultural soils (IPCC 1997). SOC storage increased with setting-aside land from crop production, reducing tillage intensities, and increasing C input through cropping practices, while SOC declined through plowing-out native lands, greater tillage intensity, and decreasing C input through cropping practices.

Even though overall results were consistent with the conceptual framework developed by the IPCC (Figure 1), there were individual studies in which the management impacts differed from the expected patterns (see response ratios on Figures 2, 3 and 4). For example, several case studies did not find an increase in SOC storage with adoption of no-till management compared to conventional tillage (Figure 3) but there are plausible reasons that explain the lack of response. First, time is a factor in measuring a significant change in SOC storage. For example, McCarty et al. (1998) found that soils did not take on the expected characteristics of a no-till system for at least 3 years. Second, even with sufficient time, a change in management may not impact SOC storage due to concomitant changes in other variables that affect C inputs and outputs from a cropland soil. For example, Halvorson et al. (2002) found that no-till had little impact on SOC storage in dry climates if the cropping system had a year of bare summer-fallow, presumably due to enhanced decomposition during fallow that negated any benefit of reduced soil disturbance. West and Post (2002) also concluded that implementation of no-till had a much smaller impact on SOC storage with bare-summer fallow in the rotation, relative to a variety of other continuous cropping rotations. Duiker and Lal (1999) found that changing tillage practices to enhance SOC storage under a moist climate regime can depend on residue production and C input under the new management system. Similarly, Wander et al. (1998) speculated that differences in residue production at one of their study sites led to greater storage of SOC under conventional tillage management than no-till. Consequently, the impact of tillage and other management practices will not change the C balance in some soils as expected based on the IPCC conceptual framework, although these cases are apparently atypical according to our literature review.

Setting-aside land from crop production is possibly the most efficient way to sequester C in agricultural soils, but this practice typically leads to a slower rate of gain in SOC storage than the losses following plowing out of native grassland or forest (Ihori et al. 1995; Burke et al. 1995; Reeder et al. 1998; Potter et al. 1999; Baer et al. 2000). There were a few sites though, in which short-term gains (<20 years) in SOC appeared to increase the total storage above the amounts found under native vegetation. Although we are not able to rule out the possibility that exceptional gains in SOC had occurred at these sites, this result was more likely an artifact of our calculation. Native vegetation is the baseline reference condition for the IPCC method in assessing the relative effect of setting-aside land on SOC storage. However, several of the studies had addressed the effect of setting-aside land relative to SOC storage under long-term cultivation, and so we approximated the SOC stock for the native baseline in those cases (see Methods). Most of the studies in which SOC storage appeared higher under set-asides than native vegetation was a consequence of this approximation, and therefore part of the uncertainty for estimating change in SOC storage that is inherent in the IPCC method using the current field data.

Through this analysis, we synthesized the available data from studies evaluating agricultural management impacts on SOC storage. Of course, some management impacts are not fully understood with regards to how they alter the C flux between the atmosphere and soil. As such, these aspects need further research, particularly since agricultural management may be used to mitigate greenhouse emissions.

One of those issue deals with the fate of eroded C, which is currently unresolved with regards to estimating management impacts on SOC storage. For example, long-term cultivation with conventional tillage relative to native lands or no-till management has been shown to decrease SOC storage by reducing aggregate stability (Elliott 1986; Jastrow 1996; Jastrow et al. 1998; Six et al. 1998, 2000, 2002) and increasing erosion (Bauer and Black 1981; Karlen et al. 1994; Doran et al. 1998). Reduced aggregate stability increases decomposition and therefore generates fluxes of CO_2 to the atmosphere. However, it is more difficult to determine how erosional losses of SOC affect the net CO_2 flux to the atmosphere. Lal et al. (1998) suggested that 80% of eroded SOC is not oxidized and returned to the atmosphere. While much of that carbon is moved short distances and re-deposited within agricultural fields (and therefore would not influence SOC stock estimates or the resulting factor values from this analysis), over longer times scales erosional processes lead to a net transfer of soil from uplands into water impoundments (e.g., lakes) and wetlands (Harden et al. 1999; Manies et al. 2001; Smith et al. 2001), and furthermore extreme events such as floods and windstorms can hasten this activity. This represents a net sink for carbon that is not included in our factor values because we are assuming that the changes SOC stocks between different land use and management conditions represent the net flux of CO_2 between the biosphere and atmosphere. There is little doubt that C sequestration occurs with no-till management and setting-aside cropland due to improved soil structure, in addition to the fact that carbon is lost through cultivation of forests and grasslands as a result of diminishing the soil structure that developed under native conditions. However, the amplitude of these impacts may be smaller than we have estimated, depending on the fate of eroded C that is transferred into water impoundments and wetlands.

Another key issue is the effect that management has below the plow layer or Ap horizon (~20–25 cm), which could not be resolved in this analysis due to a lack of studies measuring the impacts at depths deeper than 30 cm. Traditionally researchers have thought that agricultural practices mostly impacted the upper part of the profile where plowing occurs and the majority of SOC is concentrated. A few studies have questioned this expectation, though. For example, Yang and Wander (1999) found that there was no significant differences in SOC storage for the top meter of the soil profile between fields that were managed with reduced or no-till compared to those managed with conventional tillage, even though there were significant differences at the surface. However, lack of differences in the top meter may have been the result of random variation in C content of subsurface horizons that overwhelmed significant trends at the surface (Yang and Kay 2001). In a separate analysis, Mikhailova et al. (2000) found significant declines in SOC storage to a depth of 60 cm as a result of long-term cultivation, presumably due to the loss of C input from deep-rooted plants that were found in neighboring grasslands. This is an important issue that deserves further research to resolve which types of management changes are likely to have impacts deeper in the profile than the plow layer, and the mechanisms involved.

We have provided quantitative estimates for the impact of agricultural management on SOC storage that can be used for carbon accounting with the IPCC method by nations that do not have country-specific estimates for management effects or a more refined approach for conducting a national inventory (IPCC 2004). Based on our synthesis, agricultural lands can potentially sequester C and mitigate greenhouse gas emissions through adoption of reduced and no-till management, use of high C input rotations that include hay, legumes, pasture, cover crops, irrigation or organic amendments, setting-aside lands from cropland production, and through cropping intensification. Moreover, implementation of these practices will generally sequester more C in agricultural soils of tropical than temperate regions, and under moist compared to dry climatic conditions.

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Appendix 1. Published studies that were used to analyze the impact of agricultural management on SOC storage

Study	Location	Time Span (yr)	Depth (cm)	Tillage[1]	Input[2]	Long-Term Cultivat.	Set-aside
Agbenin and Goladi (1997)	Samaru, Northern Guinea, Nigeria	45	30		HM	X	
Ahl et al. (1998)	Eschwege, Hessia, Germany	9	30,50	RT			
Alvarez et al. (1998)	Pampa, Argentina	15	20	NT			
Angers et al. (1995)	St. Lambert, Quebec, Canada	11	24	RT			
Angers et al. (1997)	Charlottetown, P.E.I., Canada	8	60	RT			
	Delhi, Ontario, Canada	4	60	NT			
	Harrington, P.E.I., Canada	8	60	NT			
	Harrow, Ontario, Canada	11	60	NT			
	La Pocatiere, Quebec, Canada	6	60	NT			
	Normandin, Quebec, Canada	3,4	60	NT,RT			
	Ottawa, Ontario, Canada	5	60	NT			
Baer et al. (2000)	Gage and Saline Counties, Nebraska, USA	10	10				X
Balesdent et al. (1990)	Boigneville, France	17	30	NT			
Barber et al. (1996)	Santa Cruz, Bolivia	4	15	NT			
		5	15	RT			
Bauer and Black (1981)	Grant County, North Dakota, USA	25	45.7	RT			
Bayer et al. (2000)	Eldorado do Sul, Brazil	9	30	NT	H		
Bayer et al. (2002)	Eldorado do Sul, Brazil	9	17.5	NT			
Beare et al. (1994)	Athens, Georgia, USA	13	15	NT			

Beyer (1994)	Germany	336	70			X	
Black and Tanaka (1997)	Morton County, North Dakota, USA	6	91.2	NT,RT	L		
Bordovsky et al. (1999)	Munday, Texas, USA	3	10		H,L		
		8	10	RT	H,L		
Borin et al. (1997)	Legnaro, Italy	3	40	NT			
		7	40	RT			
Borresen and Njos (1993)	Tune, Norway	13	20	RT			
Bowman and Anderson (2002)	Northeastern Colorado, USA	30	15			X	
		4	15	NT,RT			
		8	15				X
Bremer et al. (1994)	Lethbridge, Alberta, Canada	41	30		L		
		7	30				X
Burke et al. (1995)	Weld County, Colorado, USA	53	10			X	X
Buschiazzo et al. (1998)	Cordoba, Argentina	11	5	RT			
	La Pampa, Argentina	9	5	NT			
	Northwest Buenos Aires, Argentina	4	5	NT			
	South Buenos Aires, Argentina	7	20	RT			
	Southwest Buenos Aires, Argentina	7	5	NT			
Buyanovsky et al. (1987)	Columbia, Missouri, USA	96	50			X	
Buyanovsky and Wagner (1998)	Columbia, Missouri, USA	25	20	NT	H,HM		
Cambardella and Elliott (1994)	Sidney, Nebraska, USA	20	20			X	

Appendix 1. Continued.

Study	Location	Time Span (yr)	Depth (cm)	Tillage[1]	Input[2]	Long-Term Cultivat.	Set-aside
Campbell and Zentner (1997)	Swift Current, Saskatchewan, Canada	10,15,18,24	15		L		
Campbell et al. (1991)	Melfort, Saskatchewan, Canada	30	15		L,H		
Campbell et al. (1996)	Stewart Valley, Saskatchewan, Canada	4,8,12	15	NT	L		
Campbell et al. (1997)	Indian Head, Saskatchewan, Canada	30	15		L,H		
Campbell et al. (1999)	Swift Current, Saskatchewan, Canada	5,9,13	15	NT	L		
Campbell et al. (2000)	Swift Current, Saskatchewan, Canada	10	30		L		
Carter (1991)	Charlottetown, P.E.I., Canada	2	20	NT,RT			
Carter et al. (1988)	Charlottetown, P.E.I., Canada	2	20	NT			
Carter et al. (2002)	Charlottetown, P.E.I., Canada	5	16	NT			
Chan and Mead (1988)	Cowra, NSW, Australia	2	15	NT			
		25	15				X
Chan et al. (1992)	Wagga Wagga, NSW, Australia	10	20	NT			
Chaney et al. (1985)	Tadcaster, North Yorkshire, Great Britian	5,7,9	20	NT			
Clapp et al. (2000)	Rosemount, Minnesota, USA	13	30	RT,NT			
Collins et al. (1999)	Lexington, Kentucky, USA	22	50			X	
Corazza et al. (1999)	Cerrado region, Federal District, Brazil	15	100	NT			
Costantini et al. (1996)	Marcos Juarez, Cordoba, Argentina	6	5	RT,NT			

Dalal (1989)	Warwick, Queensland, Australia	13	120	NT			
Dalal and Mayer (1986)	Chinchilla/Dalby, Queensland, Australia	26	10			X	
Dalal et al. (1991)	Warwick, Queensland, Australia	20	10		L		
Dick and Durkalski (1997)	Wooster, Ohio, USA	31	30	NT	H		
Dick et al. (1997)	Wooster, Ohio, USA	9	45	RT,NT	H		
Doran et al. (1998)	Sidney, Nebraska, USA	11	30.5	RT,NT			
		22	20	NT			
		23	20	RT			
Duiker and Lal (1999)	Columbus, Ohio, USA	7	10	RT,NT			
Edwards et al. (1992)	Crossville, Alabama, USA	11	20	NT			
Eghball et al. (1994)	Lincoln, Nebraska, USA	11	30	RT,NT			
Fleige and Baeumer (1974)	Gottingen, Germany	5,6	30	NT			
Follett and Peterson (1988)	Sidney, Nebraska, USA	16,17	20	RT,NT			
Follett et al. (1997)	Akron, Colorado, USA	23	60			X	
	Sydney, Nebraska, USA	84	60			X	
Follett et al. (2001)	Akron, Colorado, USA	6	30				X
	Boley, Oklahoma, USA	10	30				X
	Bushland, Texas, USA	8	30				X
	Columbia, Missouri, USA	7	30				X
	Dalhart, Texas, USA	8	30				X
	Dorothy, Minnesota, USA	7	30				X
	Glencoe, Minnesota, USA	9	30				X

Appendix 1. Continued.

Study	Location	Time Span (yr)	Depth (cm)	Tillage[1]	Input[2]	Long-Term Cultivat.	Set-aside
	Indianola, Iowa, USA	8	30				X
	Lincoln, Nebraska, USA	6	30				X
	Mandan, North Dakota, USA	10	30				X
	Medina, Minnesota, USA	10	30				X
	Roseau, Minnesota, USA	7	30				X
	Sidney, Montana, USA	5	30				X
	Vinson, Oklahoma, USA	10	30				X
Franzluebbers and Arshad (1996)	Alberta, Canada	4,6	20	NT			
	British Columbia, Canada	7,16	20	NT			
Franzluebbers et al. (1995)	Williamson County, Texas, USA	10	20	NT			
Franzluebbers et al. (1999)	Watkinsville, Georgia, USA	4	15	NT			
Freitas et al. (2000)	Goias, Brazil	5	40	NT			
Freixo et al. (2002)	Passo Fundo, Rio Grande do Sul, Brazil	11	30	NT	H		
Gebhart et al. (1994)	Atwood, Kansas, USA	5	300				X
	Big Springs, Texas, USA	5	300				X
	Colby, Kansas, USA	5	300				X
	Seminole, Texas, USA	5	300				X
	Valentine, Nebraska, USA	5	300				X
Ghuman and Sur (2001)	Ludhiana, Punjab, India	5	15	RT	L		
Girma (1998)	Awash River Valley, Ethiopia	24	200			X	
Graham et al. (2002)	Durban, KwaZulu-Natal, South Africa	59	30		L		

Grandy et al. (2002)	Presque Isle, Maine, USA	23	4,5		HM		
Gregorich et al. (1996)	Woodslee, Ontario, Canada	32	40			X	
Halvorson et al. (1997)	Akron, Colorado, USA	15	20	NT			
Halvorson et al. (2002)	Mandan, North Dakota, USA	12	30.4	NT	L		
Hansmeyer et al. (1997)	Rosemount, Minnesota, USA	4	7.5	RT,NT			
Hao et al. (2001)	Lethbridge, Alberta, Canada	4	30	RT			
Harden et al. (1999)	Tate and Panola Counties, Mississippi, USA	127	40			X	
Havlin and Kissel (1997)	Manhattan, Kansas, USA	11	15	NT			
Hendrix (1997)	Athens, Georgia, USA	4,5,6,7,8,10,12	21	NT			
Hernanz et al. (2002)	Alcala de Henares, Madrid, Spain	11	40	RT,NT	H		
Hulugalle (2000)	Narrabri, NSW, Australia	5,8	60	RT			
Hussain et al. (1999)	Dixon Springs, Illinois, USA	6,7	15	RT,NT			
Ihori et al. (1995)	Weld County, Colorado, USA	50	30			X	X
Janzen (1987)	Lethbridge, Alberta, Canada	33	30		L		
Jastrow et al. (1998)	Batavia, Illinois, USA	1,4,8,10	10				X

Appendix 1. Continued.

Study	Location	Time Span (yr)	Depth (cm)	Tillage[1]	Input[2]	Long-Term Cultivat.	Set-aside
Karlen et al. (1994)	Lancaster, Wisconsin, USA	12	5	RT,NT			
Karlen et al. (1998)	Nashua, Iowa, USA	15	20	RT,NT			
Karlen et al. (1999)	Butler County, Iowa, USA	6	7.5				X
	Henry County, Iowa, USA	2	7.5				X
	Minnesota, USA	6	7.5				X
	North Dakota, USA	5	7.5				X
	Washington, USA	5	7.5				X
Kushwaha et al. (2000)	Varanasi, India	1	10	RT,NT			
Lal (1998)	Ibadan, Nigeria	2,5,7	10		L		
		2,7	10	NT			
Lal et al. (1994)	Wooster, Ohio, USA	29	15	RT,NT			
Larney et al. (1997)	Lethbridge, Alberta, Canada	8	15		L		
		7,8,15	15	NT			
		15	15	RT			
Lilienfein et al. (2000)	Minas Gerais, Brazil	2	200	NT			
McCarty et al. (1998)	Maryland, USA	3	20	NT			
Mielke et al. (1986)	Elwood, Illinois, USA	6	30	NT			
	Lincoln, Nebraska, USA	6	30	NT			
	Waseca, Minnesota, USA	6,11	30,15	NT			
Mikhailova et al. (2000)	Kursk, Russia	100	118			X	
Mrabet et al. (2001)	Sidi El Aydi, Morrocco	11	20	NT			

Nyborg et al. (1995)	Breton, Alberta, Canada	11	15	NT			
	Ellerslie, Alberta, Canada	11	15	NT			
Parfitt et al. (1997)	New Zealand	20,21,21	20			X	
Paustian and Elliott unpublished	Bushland, Texas, USA	12	100		L		
	Griffin, Georgia, USA	18	100	NT			
	Hickory Corners, Michigan, USA	53	100			X	
		6	75	NT			
	Hoytville, Ohio, USA	29	100	NT			
	Indian Head, Saskatchewan, Canada	35	100		L		
	Kutztown, Pennsylvania, USA	11	100		H		
	Lethbridge, Alberta, Canada	41	100		L		
	Manhattan, Kansas, USA	92	90			X	
		17	100	RT,NT			
	Melfort, Saskatchewan, Canada	35	50		L		
	Sidney, Nebraska, USA	22	100			X	
	South Charleston, Ohio, USA	30	100	RT,NT			
	Sterling, Colorado, USA	7	100	NT			X
	Stratton, Colorado, USA	7	100				X
	Swift Current, Saskatchewan, Canada	26	100	NT	L		
		26	25			X	
	Walsh, Colorado, USA	7	100	NT	L		X
	West Lafeyette, Indiana, USA	12	100	RT,NT			
	Wooster, Ohio, USA	30	75	RT,NT			
Pennock and van Kessel (1997)	Saskatchewan, Canada	70	45			X	
Pierce and Fortin (1997)	East Lansing, Michigan, USA	7,11	10	NT			
Potter et al. (1997)	Bushland, Texas, USA	10	20		L		

Appendix 1. Continued.

Study	Location	Time Span (yr)	Depth (cm)	Tillage[1]	Input[2]	Long-Term Cultivat.	Set-aside
Potter et al. (1999)	Burleson, Texas, USA	100	120			X	
		26	120				X
	Riesel, Texas, USA	100	120			X	
		60	120				X
	Temple, Texas, USA	100	120			X	
		6	120				X
Powlson and Jenkinson (1982)							
	Boxworth, Great Britain	6	25	NT			
	Tadcaster, Great Britain	8	25	NT			
	Penicuik, Great Britain	10	25	NT			
	Rothamsted, Great Britain	5	25	NT			
Rasmussen and Albrecht (1997)	Pendleton, Oregon, USA	27,39	20	RT			
		39	20		L		
		59	20				X
	Moscow, Idaho, USA	30	30		HM,L		
Reeder et al. (1998)	Arvada, Wyoming, USA	63	25			X	
		4	25				X
	Keeline, Wyoming, USA	63	28			X	
		4	28				X
Rhoton et al. (1993)	Auburn, Alabama, USA	5	15	NT			
	Jackson, Tennessee, USA	9	15	NT			
	Verona, Mississippi, USA	5	15	NT			
	Watkinsville, Georgia, USA	15	15	NT			
Robles and Burke (1998)	Chugwater, Wyoming, USA	6	5				X

Ross and Hughes (1985)	Palmerston North, New Zealand	5	20	RT,NT			
Sa et al. (2001)	Ponta Grossa, Parana, Brazil	22	40	NT			
Saffigna et al. (1989)	Biloela, Queensland, Australia	5	10	NT			
Saggar et al. (2001)	Palmerston North, New Zealand	20	10			X	
		34	10			X	
Sainju et al. (2002)	Fort Valley, Georgia, USA	1,2,3,4,5	20	RT,NT	L		
		1,2,3,4,5,6	20				
SalinasGarcia et al. (1997)	Corpus Christi, Texas, USA	16	20	RT,NT			
Schiffman and Johnson (1989)	Virginia, USA	53	33			X	
Sherrod et al. (in press)	Sterling, Colorado, USA	12	20		L		X
	Stratton, Colorado, USA	12	20		L		X
	Walsh, Colorado, USA	12	20		L		X
Sidhu and Sur (1993)	Punjab Ag University, India	5	15		H		
Six et al. (1998)	Sidney, Nebraska, USA	25	20			X	
Six et al. (2000)	Lexington, Kentucky, USA	25	20	NT		X	
	Hickory Corners, Michigan, USA	9	20	NT			
	Wooster, Ohio, USA	33	20	NT			
	Sidney, Nebraska, USA	25	20	NT			
Slobodian et al. (2002)	St. Denis, Saskatchewan, Canada	49	120			X	
Solomon et al. (2002)	Wushwush, Ethiopia	25	10			X	
	Munesa, Ethiopia	30	10			X	
Sparling et al. (2000)	Oamaru, South Island, New Zealand	40	20			X	

Appendix 1. Continued.

Study	Location	Time Span (yr)	Depth (cm)	Tillage[1]	Input[2]	Long-Term Cultivat.	Set-aside
Stenberg et al. (2000)	Sundby, Sweden	8	24	RT			
Taboada et al. (1998)	Rolling Pampas, Argentina	4	10	NT			
Tiessen et al. (1982)	Blaine Lake, Saskatchewan, Canada	60,90	30			X	
	Bradwell, Saskatchewan, Canada	65	30			X	
	Sutherland, Saskatchewan, Canada	70	31			X	
Unger (2001)	Armstrong County, Texas, USA	38,50	30			X	
		10	30				X
	Briscoe Country, Texas, USA	10,43	30				X
	Carson County, Texas, USA	40,10	30			X	X
	Dallam County, Texas, USA	40,10	30			X	X
	Hutchinson County, Texas, USA	40,10	30			X	X
	Moore County, Texas, USA	40,10	30			X	X
	Oldham County, Texas, USA	10,38	30			X	X
	Potter County, Texas, USA	78,10	30			X	X
	Swisher County, Texas, USA	48,10	30			X	X
Voroney et al. (1981)	Indian Head, Saskatchewan, Canada	70	50			X	
Wander et al. (1998)	DeKalb, Illinois, USA	10	30	NT			
	Monmouth, Illinois, USA	10	30	NT			
	Perry, Illinois, USA	10	30	NT			
Wanniararchie et al. (1999)	Delhi, Ontario, Canada	6	50	NT			
		14	50	RT			
Westerhof et al. (1998)	Cerrado region, Brazil	5	10		H		

Yang and Kay (2001)	Southern Ontario, Canada	19	60	NT	
Yang and Wander (1999)	Urbana, Illinois, USA	11	90	RT,NT	
Zhang et al. (1988)	Hardin County, Iowa, USA	120	20		X

[1]RT indicates that the study dealt with reduced tillage impacts, and NT indicates that the study dealt with no-till impacts.
[2]H indicates that the study dealt with high input rotations, L indicates that the study dealt with low input rotations, and HM indicates that the study dealt with high input rotations that were receiving organic amendments.

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