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No-tillage lessens soil CO_2 emissions the most under arid and sandy soil conditions: results from a meta-analysis

Khatab Abdalla[1,2], Pauline Chivenge[1,3], Philippe Ciais[4], and Vincent Chaplot[1,5]

[1]School of Agricultural, Earth & Environmental Sciences, CWRR, Rabie Saunders Building, University of KwaZulu-Natal, Scottsville, 3209, South Africa
[2]Environment, Natural Recourses and Desertification Research Institute, National Centre for Research, P.O. Box 6096, Khartoum, Sudan
[3]ICRISAT, Matopos Research Station, P.O. Box 776, Bulawayo, Zimbabwe
[4]IPSL – LSCE, CEA CNRS UVSQ, Centre d'Etudes Orme des Merisiers, 91191, Gif-sur-Yvette, France
[5]Institut de Recherche pour le Développement (IRD), Laboratoire d'Océanographie et du Climat (LOCEAN), UMR 6159 CNRS/IRD/UPMC/MNHN, 4, place Jussieu 75252, Paris CEDEX 05, France

Correspondence to: Vincent Chaplot (chaplot@ird.fr)

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Abstract. The management of agroecosystems plays a crucial role in the global carbon cycle with soil tillage leading to known organic carbon redistributions within soils and changes in soil CO_2 emissions. Yet, discrepancies exist on the impact of tillage on soil CO_2 emissions and on the main soil and environmental controls. A meta-analysis was conducted using 46 peer-reviewed publications totaling 174 paired observations comparing CO_2 emissions over entire seasons or years from tilled and untilled soils across different climates, crop types and soil conditions with the objective of quantifying tillage impact on CO_2 emissions and assessing the main controls. On average, tilled soils emitted 21 % more CO_2 than untilled soils, which corresponded to a significant difference at $P < 0.05$. The difference increased to 29 % in sandy soils from arid climates with low soil organic carbon content ($SOC_C < 1$ %) and low soil moisture, but tillage had no impact on CO_2 fluxes in clayey soils with high background SOC_C (> 3 %). Finally, nitrogen fertilization and crop residue management had little effect on the CO_2 responses of soils to no-tillage. These results suggest no-tillage is an effective mitigation measure of carbon dioxide losses from dry land soils. They emphasize the importance of including information on soil factors such as texture, aggregate stability and organic carbon content in global models of the carbon cycle.

1 Introduction

The evidence for climate change is irrefutable, and the necessity of mitigating climate change is now accepted. Yet, there are still large uncertainties on the effectiveness of the measures that could be taken to reduce greenhouse gas (GHG) emissions by land-use management (Smith et al., 2008; Ciais et al., 2011).

There are several reasons for these uncertainties. While inventories can be made of the different carbon pools (Bellamy et al., 2005), carbon pool changes are small and difficult to detect; they require sampling programs with periodic revisits over many years. Thus, the magnitude and variability of CO_2 fluxes, both sinks and sources, between the soil and the atmosphere are difficult to quantify and they may not have been accurately assessed. This is particularly the case for CO_2 fluxes associated with land use and land management, such as deforestation and changes in agricultural practice (Al-Kaisi and Yin, 2005; Alluvione et al., 2009; Dilling and Failey, 2012).

Soils are the largest terrestrial pool of carbon (C), storing 2344 Pg C (1 Pg = 1 billion tonnes) of soil organic carbon (SOC) in the top 3 m (Jobbágy and Jackson, 2000). Tilling the soil before planting for seedbed preparation and weeding has been a common practice in agriculture since Neolithic times (McKyes, 1985). This technique is energy intensive and also affects SOC stocks. Tilling changes the balance between organic carbon put into the soil by plants and rendered available for soil micro-organisms, and carbon output as greenhouse gases (GHGs) due to organic matter decomposition (Rastogi et al., 2002). Soil tillage may also lead to the vertical and lateral export of particulate and dissolved organic carbon by leaching and erosion (Jacinthe et al., 2002; Mchunu et al., 2011).

Soil tillage is estimated to have decreased SOC stocks by two-thirds from pre-deforestation levels (Lal, 2003). But this estimate is highly uncertain, due to the lack of detailed site-level meta-analysis for different climates, soil types and management intensities.

Six et al. (2000, 2004) reported that tillage induces soil disturbance and disruption of soil aggregates, exposing the protected SOC to microbial decomposition and thus causing carbon loss from soils through CO_2 emissions and leaching. Tillage is also responsible for soil compaction, soil erosion and loss of soil biodiversity (Wilson et al., 2004). In some instances, tillage is thought to have caused a net sink of atmospheric CO_2, for instance by displacing SOC to deeper soil horizons or accumulation areas where it decomposes more slowly (Baker et al., 2007; Van Oost et al., 2007). Soil tillage also modifies the mineralization rates of nutrients, which feeds back on soil carbon input, implying that the effect of tillage on the balance of SOC needs to be considered at ecosystem level (Barré et al., 2010).

At the present time, tillage is being increasingly abandoned as the use of mechanized direct planters becomes widespread and weed control is performed with herbicides or in a more ecologically friendly way by using cover crops and longer crop rotations.

The consequences of this change in practice on soil properties and soil functioning are numerous. Importantly, it also raises the unsolved question: what is the impact of tillage abandonment on GHG emissions and climate change? Common wisdom is that no-tillage (or zero-tillage) agriculture enhances soil carbon stocks (Peterson et al., 1998; Six et al., 2002; West and Post, 2002; Varvel and Wilhelm, 2008) by reducing soil carbon loss as CO_2 emission (Paustian et al., 1997; West and Post, 2002; Dawson and Smith, 2007). For instance, Paustian et al. (1997) reviewed 39 paired comparisons and reported that abandonment of tillage increased SOC stocks in the 0–0.3 m layer by an average of 258 $g\,C\,m^{-2}$ (i.e. 8 %). Ussiri and Lal (2009) observed a 2-fold increase of SOC stocks in the top 0.3 m of soil (800 vs. 453 $g\,C\,m^{-2}$) after 43 years of continuous *Zea mays* (maize) under no-tillage compared to tillage. Virto et al. (2012), in a meta-analysis based on 92 paired comparisons. reported that SOC stocks were 6.7 % greater under no-tillage than tillage.

While a consensus seemed to exist on the potential of no-tillage for carbon sequestration and climate change mitigation, several voices alerted the scientific and policy communities to some possible flaws in early reports (Royal Society, 2001; VandenBygaart and Angers, 2006; Baker et al., 2007; Luo et al., 2010; Dimassi et al. 2014; Powlson et al., 2014). VandenBygaart and Angers (2006) indicated that the entire plow depth had to be considered for not overstating zero-tillage impact on SOC storage. To our knowledge, Baker et al. (2007) were the first to point out that the studies concluding on carbon sequestration under no-tillage management had only considered the topsoil (to a maximum of 0.3 m), while plants allocate SOC to much greater depths. False conclusions may be drawn if only carbon in the topsoil is measured. Using 69 paired experiments worldwide where soil sampling depth extended to 1.0 m, Luo et al. (2010) found that conversion from tillage to no-tillage resulted in significant topsoil SOC enrichment, but did not increase the total SOC stock in the whole soil profile. Dimassi et al. (2014) even reported SOC losses over the long term.

Evidence for greater CO_2 emissions from land under tillage as opposed to a no-tillage regimen has been widely reported (e.g. Reicosky, 1997; Al-Kaisi and Yin, 2005; Bauer et al., 2006; Sainju et al., 2008; Ussiri and Lal, 2009). For instance, in a study performed in the US over an entire year, Ussiri and Lal (2009) found that, tillage emits 11.3 % (6.2 vs. 5.5 Mg of CO_2-carbon per hectare per year, CO_2-$C\,ha^{-1}\,yr^{-1}$) more CO_2 than no-tillage. Similarly, all the field surveys by Alluvione et al. (2009) reported that land under tillage had 14 % higher CO_2 emissions than land with no-tillage. Al-Kaisi and Yin (2005) found this difference to be as much as 58 %. A few in situ studies, however, found CO_2 emissions from no-tillage soils to be similar to those from tilled soils (Aslam et al., 2000; Oorts et al., 2007; Li et al., 2010). However, Hendrix et al. (1988) and Oorts et al. (2007) found greater CO_2 emissions from untilled compared to tilled soils, with Oorts et al. (2007) reporting that no-tillage increased CO_2 emissions by 13 % compared to tillage. In a further example, Cheng-Fang et al. (2012) showed that in central China, no-tillage increased soil CO_2 emissions by 22–40 % compared with tillage. Oorts et al. (2007) attributed the larger CO_2 emissions from no-tilled soil compared to tilled soil to increased decomposition of the weathered crop residues lying on the soil surface. Crop residue management has been shown to greatly impact CO_2 emissions from soils under both tillage and no-tillage (Oorts et al., 2007; Dendooven et al., 2012). Jacinthe et al. (2002) reported annual CO_2 emissions to be 43 % higher with tillage compared to no-tillage with no mulch, but found a 26 % difference for no-tillage with mulch. Some other authors associated the changes in CO_2 emissions following tillage abandonment to shifts in nitrogen fertilization application and in crop rotations (Al-Kaisi and Yin, 2005; Álvaro-Fuentes et al., 2008; Cheng-Fang et al., 2012). Sainju et al. (2008) working in North Dakota pointed to CO_2 flux differences between tilled and untilled soils only for fertilized fields, while other studies pointed to the absence of nitrogen impact (Drury et al., 2006; Cheng-Fang et al., 2012). Crop type and crop rotation may also constitute important controls on the CO_2 efflux differences between tillage and no-tillage, mainly through differences in root biomass and its respiration and nitrogen availability (Amos et al., 2005; Álvaro-Fuentes et al., 2008). Omonode et al. (2007) found a 16 % difference in CO_2 outputs between tillage and no-tillage under continuous maize, while Sainju et al. (2010b) found no difference between continuous barley and barley–pea rotations.

Micro-climatic parameters such as soil temperature and precipitation are other likely controls of the response of soil CO_2 emissions to tillage (Flanagan and Johnson, 2005; Lee et al., 2006; Oorts et al., 2007). These controls also need further appraisal.

The existence of research studies from different soil and environmental conditions worldwide opens the way for a more systematic assessment of tillage impact on soil CO_2 emissions and their controls. Meta-analysis is commonly used for combining research findings from independent studies and offers a quantitative synthesis of the findings (Rosenberg et al., 2000; Borenstein et al., 2011). This method has been used here in order to assess the effects of background climate (arid to humid), soil texture (clayey to sandy), crop types (maize, wheat, barley, paddy rice, rapeseed, fallow and grass), experiment duration, nitrogen fertilization, crop residue management and crop rotations on the CO_2 emission responses of soils following tillage abandonment. CO_2 emissions from soil with tillage and no-tillage were compared for 174 paired observations across the world.

2 Materials and methods

2.1 Database generation

A literature search identified papers considering in situ soil CO_2 emissions and topsoil (0–0.03 m depth) SOC changes under tillage and no-tillage management regimes. Google, Google scholar, Science Direct, Springerlink, and SciFinder were used. In order to make the search process as efficient as possible, a list of topic-related keywords was used such as "soil carbon losses under tillage compared to no-tillage", "soil CO_2 emissions under tillage and no-tillage", "land management practices and greenhouse gases emissions", "land management effects on CO_2 emissions", "effects of tillage vs. no-tillage on soil CO_2 emissions" and "SOC". Many studies reported soil CO_2 emissions and SOC for cropland systems, but only those that reported CO_2 emissions measured in the field for both tillage and no-tillage from the same crop and during the same period were used. In addition, we selected only studies that consistently reported total soil respiration (heterotrophic + belowground autotrophic respiration). The crops considered in this study were maize, wheat, barley, oats, soybean, paddy rice and fallow. The practices considered as tillage in this review are those that involve physical disturbance of the topsoil layers for seedbed preparation, weed control, or fertilizer application. Consequently, conventional tillage, reduced tillage, standard tillage, minimum tillage and conservation tillage were all considered as tillage. However, only direct seeding and drilling were considered as no-tillage, among different practices reported in the reviewed literature. The studies used in the meta-analysis covered 13 countries (USA, Spain, Brazil, Canada, China, Denmark, France, Finland, New Zealand, Lithuania, Mexico, Argentina, and Kenya). A total of 46 peer-reviewed papers with 175 comparisons for soil CO_2 emissions and 162 for SOC content (SOC_C) were identified. Table 1 summarizes information on site location, climatic conditions, crop rotation systems, and average CO_2 emissions under tilled and untilled soils. Most of the data (37 %) came from USA, followed by Canada, China and Spain (11 % each), and Brazil (9 %). There was only one study from Africa, conducted in Kenya by Baggs et al. (2006).

Several soil variables were considered, as follows: SOC_C (%), soil bulk density (ρb, g cm^{-3}), and soil texture (clay, silt, and sand, %) in the 0–0.03 m layer. In addition, mean annual temperature (MAT, °C) and mean annual precipitation (MAP, mm), crop types, crop rotations, nitrogen fertilization rate, experiment duration and crop residue management were also considered.

Data for soil CO_2 emissions ($n = 46$) were obtained for all studies by using open chambers and reported on an area basis. Soil CO_2 emissions were directly extracted from the papers and were standardized to g CO_2-C m^{-2} yr^{-1}. Thirty-eight studies gave SOC_C for both tillage and no-tillage. Four studies (Hovda et al., 2003; Álvaro-Fuentes et al., 2008; Lee et al., 2009; Dendooven et al., 2012) gave SOC_C, in term of the mass of carbon in the 0–0.03 m layer and per unit area (kg C m^{-2}). Finally, for the four remaining studies, SOC_C was extracted from other publications describing measurements at the same site. SOC_C was estimated from soil organic carbon stocks (SOC_S kg C m^{-2}) and bulk density following Eq. (1) by Batjes (1996):

$$SOC_S = SOC_C \times \rho b \times T(1 - \frac{PF}{100})b, \quad (1)$$

where SOC_S is the soil organic C stock (kg C m^{-2}); SOC_C is soil organic C content in the ≤ 2 mm soil material (g C kg^{-1} soil); ρb is the bulk density of the soil (kg m^{-3}); T is the thickness of the soil layer (m); PF is the proportion of fragments of > 2 mm in percent; and b is a constant equal to 0.001.

Information on MAP and MAT was extracted from the papers, but were estimated in nine studies where such information was not provided, based on the geographic coordinates of the study site and using the WORLDCLIM climatology (Hijmans et al., 2005) with a spatial resolution of 30 s. In eight studies where soil texture was only given as textural class, particle size distribution was estimated using the adapted soil texture triangle (Saxton et al., 1986).

Table 2 shows the variables used in categorizing the experimental conditions. The climatic regions were extracted directly from the papers and categorized into arid and humid

Table 1. References included in database with locations, mean annual precipitation (MAP), mean annual temperature (MAT), climate, land use, no-tillage comparisons, average tillage (T), and no-tillage (NT) CO_2 emissions.

SN.	Author (s)	Country	Comparisons	MAP mm	MAT °C	Climate	Land use	No-tillage vs.	CO_2 emissions gCO_2-C m^{-2} yr^{-1} T	NT
1	Ahmad et al. (2009)	China	2	2721	17	Humid	Rice–rapeseed	CT	857	888
2	Al-Kaisi and Yin (2005)	USA	4	889	10	Humid	Maize–soybean	ST&DT&CP&MP	292	206
3	Alluvione et al. (2009)	USA	2	383	11	Arid	Maize	CT	490	599
4	Almaraz et al. (2009a)	Canada	2	979	6	Humid	Soybean	CT	747	523
5	Almaraz et al. (2009b)	Canada	4	979	6	Humid	Maize	CT	1269	1374
6	Alvarez et al. (2001)	Argentina	1	1020	17	Humid	Wheat-soybean	CT	2154	1533
7	Álvaro-Fuentes et al. (2008)	Spain	24	415	15	Arid	Wheat–barley–fallow–rapeseed	CT&RT	2311	1891
8	Aslam et al. (2000)	New Zealand	1	963	13	Humid	Maize	MP	2306	2281
9	Baggs et al. (2006)	Kenya	2	1800	24	Humid	Maize–fallow	CT	171	215
10	Brye et al. (2006)	USA	4	1282	16	Humid	Wheat–soybean	CT	3264	2604
11	Carbonell-Bojollo et al. (2011)	Spain	3	475	25	Arid	Wheat–pea–sunflower	CT	298	100
12	Chatskikh and Olesen (2007)	Denmark	2	704	7	Humid	Barley	CT&RT	117	102
13	Cheng-Fang et al. (2012)	China	4	1361	17	Humid	Rice–rapeseed	CT	636	699
14	Chavez et al. (2009)	Brazil	1	1755	19	Humid	Oats–soybean–wheat–maize	CT	464	573
15	Datta et al. (2013)	USA	1	1016	11	Humid	Maize	CT	438	634
16	Dendooven et al. (2012)	Mexico	2	600	14	Arid	Maize–wheat	CT	100	100
17	Drury et al. (2006)	USA	3	876	9	Humid	Wheat–maize–soybean	CT	575	559
18	Elder and Lal (2008)	USA	1	1037	11	Humid	Maize–wheat	MT	225	189
19	Ellert and Janzen (1999)	Canada	5	400	5	Arid	Wheat–fallow	CT&RT	406	186
20	Feizienė et al. (2010)	Lithuania	24	500	18	Humid	Wheat-rapeseed-barley-pea	CT&RT	302	296
21	Hovda et al. (2003)	Canada	2	979	6	Humid	Maize	CT	1342	1277
22	Jabro et al. (2008)	USA	1	373	14	Humid	Sugarcane	CT	3424	2247
23	Lee et al. (2009)	USA	3	564	16	Arid	Maize–sunflowers-pea	ST	933	917
24	Li et al. (2010)	China	4	1361	17	Humid	Rice–rapeseed	CT	284	328
25	Li et al. (2013)	China	2	1361	18	Humid	Rice	CT	2196	1534
26	Liu et al. (2006)	China	4	550	13	Humid	Maize	RT &PT	1340	1194
27	López-Garrido et al. (2009)	Spain	1	484	17	Arid	Wheat–sunflower–pea	CT	1080	943
28	López-Garrido et al. (2014)	Spain	3	484	17	Humid	Wheat–pea–red clover	CT	1075	887
29	Lupwayi et al. (1998)	Canada	1	336	−1	Arid	Wheat–pea–red clover	CT	621	464
30	Morell et al. (2010)	Spain	8	430	14	Arid	Barley	CT&MP	300	229
31	Mosier et al. (2006)	USA	9	382	11	Arid	Maize	CT	387	351
32	Menéndez et al. (2008)	Spain	2	350	16	Arid	Wheat–sunflower	CT	183	214
33	Omonode et al. (2007)	USA	4	588	19	Humid	Maize	MP&CP	273	268
34	Oorts et al. (2007)	France	2	650	11	Humid	Maize–wheat	CT	475	620
35	Pes et al. (2011)	Brazil	2	1721	19	Humid	wheat–soybean	CT	1387	1004
36	Regina and Alakukku (2010)	Finland	6	585	4	Humid	Barley-wheat-oats	CT	1856	2009
37	Reicosky and Archer (2007)	USA	1	301	5	Humid	Maize–soybean	MP	5807	1545
38	Ruan and Robertson (2013)	USA	1	890	10	Humid	Soybean	CT	1825	1533
39	Sainju et al. (2008)	USA	4	368	14	Arid	Barley–pea	CT	6726	4217
40	Sainju et al. (2010a)	USA	6	350	16	Humid	Barley–pea	CT	240	208
41	La Scala Jr. et al. (2001)	Brazil	4	1380	21	Humid	Maize	ROT&CP&DO&HO	1264	657
42	La Scala Jr. et al. (2005)	Brazil	4	1380	21	Humid	Maize	CT	758	518
43	La Scala Jr. et al. (2006)	Brazil	2	1380	21	Humid	Sugarcane	RT&CT	5435	2604
44	Smith et al. (2011)	USA	1	796	17	Humid	Maize–soybean	CT	141	152
45	Smith et al. (2012)	USA	4	1370	17	Humid	Maize–soybean	CT	970	935
46	Ussiri and Lal (2009)	USA	2	1037	11	Humid	Maize–soybean	CT&MT	721	500

Table 2. Categories used in describing the experimental conditions.

Categorical variable	Level 1	Level 2	Level 3
SOC_C	Low	Medium	High
	(< 10 g kg^{-1})	(10–30 g kg^{-1})	(> 30 g kg^{-1})
Climate	Arid	Humid	
Soil texture	Clay	Loam	Sand
	(> 32 % clay)	(20–32 clay)	(< 20 % clay)
Experiment duration	< 10 years	≥ 10 years	
Nitrogen fertilizer	Low	high	
	(< 100 kg N ha^{-1})	(≥ 100 kg N ha^{-1})	
Crop residues	Removed	Returned	
Crop rotation	No rotation	Rotation	

climate (Köppen, 1936). SOC_C were categorized into three categories following Lal (1994): low (SOC_C < 10 g C kg^{-1}), medium (10–30 g C kg^{-1}), and high (> 30 g C kg^{-1}). Soil texture was categorized based on the soil textural triangle (Shirazi and Boersma, 1984) into three classes (clay, loam, and sand). Fertilization rate for this meta-analysis was classified into the categories defined by Cerrato and Blackmer (1990) as follows: low when below 100 kg N ha^{-1} and high when above 100 kg N ha^{-1}.

In addition, no-tillage treatment was classified as short duration when < 10 years, or long duration when exceeding 10 years. Crop residue was either left on the soil surface or removed after harvest with no distinction between removal proportions. Crop rotations were divided into two categories: a series of different types of crop in the same area classed as "rotation", or continuous monoculture, classed as "no rotation".

2.2 Meta-analysis

The response ratio (R) of CO_2 emissions to SOC under tillage (T) and no-tillage (NT) was calculated using Eqs. (2) and (3). As common practice, natural log of the R ($\ln R$) has been calculated as an effect size of observation (Hedges et al., 1999).

$$\ln R = \ln(CO_{2T}/CO_{2NT}) \quad (2)$$

$$\ln R = \ln(SOC_T/SOC_{NT}) \quad (3)$$

The MetaWin 2.1 software (Rosenberg et al., 2000) was used for analyzing the data and generating a bootstrapped (4999 iterations) to calculate 95 % confidence intervals. The means of effect size were considered to be significantly different from each other if their 95 % confidence intervals were not overlapping and were significantly different from zero if the 95 % level did not overlap zero (Gurevitch and Hedges, 2001).

3 Results

3.1 General statistics of soil CO_2 emissions from tilled and untilled soils

Overall, average soil CO_2 emissions computed from the 174 paired observations was 1152 g CO_2-C m^{-2} yr^{-1} from tilled soils compared to 916 g C-CO_2 m^{-2} yr^{-1} from under no-tillage (Table 3), which corresponds to a 21 % average difference, significant at $P<0.05$. The greatest soil CO_2 emission amongst the considered sites was 9125 g C-CO_2 m^{-2} yr^{-1} observed under tilled soils with barley in an arid area at Nesson Valley in western North Dakota, USA (Sainju et al., 2008). The lowest soil CO_2 emission was 11 g CO_2-C m^{-2} yr^{-1} observed under no-tillage wheat in the humid climate of Lithuania (Feizienė et al., 2011).

3.2 Controls on the response of soil CO_2 emissions to tillage

3.2.1 Climate

Tillage emitted 27 % more CO_2 than no-tillage in arid climates; while for pairs in humid climates, tillage emitted 16 % more CO_2 than no-tillage. However, the differences in CO_2 emissions between tillage and no-tillage were not statistically significant (at 0.05 confidence interval) between arid and humid climates (Fig. 1a). When compared across all studies, mean SOC_C under tillage was 10 % lower than under no-tillage (Fig. 1b). In arid climates, SOC_C in tillage was 11 % lower than no-tillage, whereas in humid climates SOC_C under tillage was only 8 % less than for no-tillage. However, the differences in SOCc between the two climatic zones were found to be non-significant.

3.2.2 Soil organic carbon content

On average, soil CO_2 emissions from tilled soils were 25 % greater compared to untilled for soils with SOC_C lower than 10 g kg^{-1} (Fig. 2). For SOC_C between 10 and 30 g kg^{-1}, tilled soils emitted an average 17 % more CO_2 than untilled ones. In the case of carbon-rich soils with SOC_C higher than 30 g kg^{-1}, there were no significant differences between tillage and no-tillage CO_2 emissions. Thus, the difference between tillage and no-tillage decreased with increasing background SOC_C. Overall, soil CO_2 emissions under no-tillage were about 5 times greater for low compared to high SOC_C.

3.2.3 Soil texture

Differences in CO_2 emissions between tilled and untilled soils were largest in sandy soils where tilled soils emitted 29 % more CO_2 than untilled soils (Fig. 3a). In clayey soils, the differences between tillage and no-tillage were much smaller with tilled soils emitting 12 % more CO_2 than untilled soils. On the other hand, SOC_C under tillage was sig-

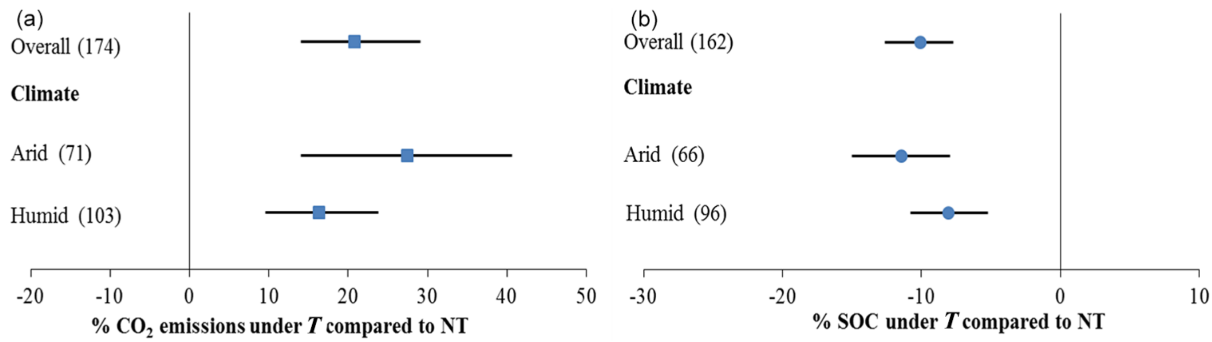

Figure 1. Percent change in **(a)** soil CO_2 emissions and **(b)** SOC in tillage (T) soil compared to no-tillage (NT) as a function of climate (arid and humid). The numbers in the parentheses indicate the direct comparisons of the meta-analysis. Error bars are 95 % confidence intervals.

Table 3. Summary statistics of mean annual precipitation (MAP), mean annual temperature (MAT), clay, soil bulk density (ρb), soil organic carbon content (SOC_C), soil organic carbon stocks (SOC_S), and CO_2 emissions ($g\,CO_2\text{-}C\,m^{-2}\,yr^{-1}$ and $g\,CO_2\text{-}C\,gC^{-1}\,yr^{-1}$) under tilled ($T$) and untilled (NT) soils.

	MAP	MAT	CLAY	ρb		SOC_C		SOC_S		CO_2 emissions			
				T	NT	T	NT	T	NT	T	NT	T	NT
	mm	°	%	$g\,cm^{-3}$		%		$kg\,m^{-2}$		$g\,CO_2\text{-}C\,m^{-2}\,yr^{-1}$		$g\,CO_2\text{-}C\,gC^{-1}\,yr^{-1}$	
Minimum	301	−1	3	0.5	0.8	0.3	0.6	0.7	1.1	33	11	0.006	0.001
Maximum	2721	25	60	1.9	1.9	8.0	7.8	9.6	10.4	9125	5986	0.823	0.118
Mean	904	15	1.3	1.3	1.3	1.3	2.9	2.9	3.1	1152	916	0.109	0.016
Median	704	16	1.3	1.3	1.3	1.1	2.5	2.5	2.7	587	533	0.071	0.012
SD	570	6	0.2	0.1	0.1	1.0	1.0	1.5	1.5	1482	1054	0.132	0.017
Skewness	1	0	−0.7	0.6	0.6	4.0	3.2	2.0	2.8	2.8	2.4	3.127	3.599
Quartile1	415	11	1.3	1.3	1.3	0.7	0.7	2.2	2.4	287	283	0.037	0.008
Quartile3	1321	18	1.4	1.4	1.4	1.3	1.7	3.3	3.3	1414	1210	0.107	0.020
Kurtosis	2	0	9.9	3.4	3.4	23.3	14.3	6.3	10.7	9.8	6.69	12.48	17.81
CV	63	41	0.1	0.1	0.1	0.8	0.4	0.5	0.5	1.29	1.15	1.214	1.018
SE	48	0	0.01	0.01	0.01	0.08	0.09	0.12	0.13	112	80	0.011	0.001

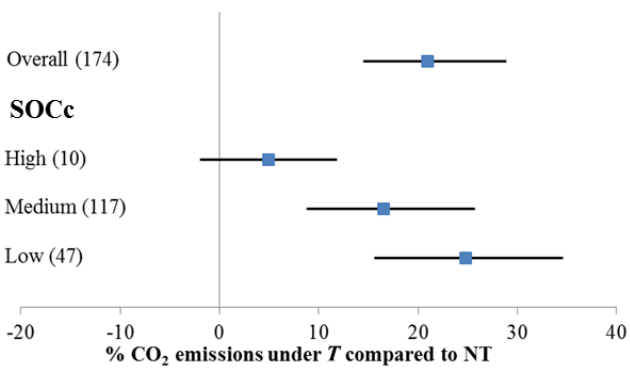

Figure 2. Percent change in CO_2 emissions in tillage (T) compared to no tillage (NT) as a function of SOC_C (low, < 10 g kg^{-1}, medium 10–30 g kg^{-1}, high >30 g kg^{-1}). The numbers in the parentheses indicate the direct comparisons of meta-analysis. Error bars are 95% confidence intervals.

nificantly lower than under no-tillage: by 17 % under sandy soils and 9 % in clayey soils (Fig. 3b). However, there were no differences between clayey and loamy soils.

3.2.4 Crop type

Soil CO_2 emissions were significantly greater in tilled compared to untilled soils for all crop types with the exception of paddy rice where there were no significant differences between tilled and untilled soils (Fig. 4a). The greatest CO_2 emission difference between tillage and no-tillage was found in fallow, with a value of 34 %.

Grouping all crop types together, SOC_C under tillage was significantly lower than under no-tillage. Among the different crops (rice, maize, soybean, wheat, and barley) a significant SOCc difference between tilled and untilled soil was only observed for maize (15 %) at one site and for rice (7.5 %). SOC_C under no-tillage was slightly greater than under tillage for soils under fallow, but the difference was not significant (Fig. 4b). Highest SOC_C differences between

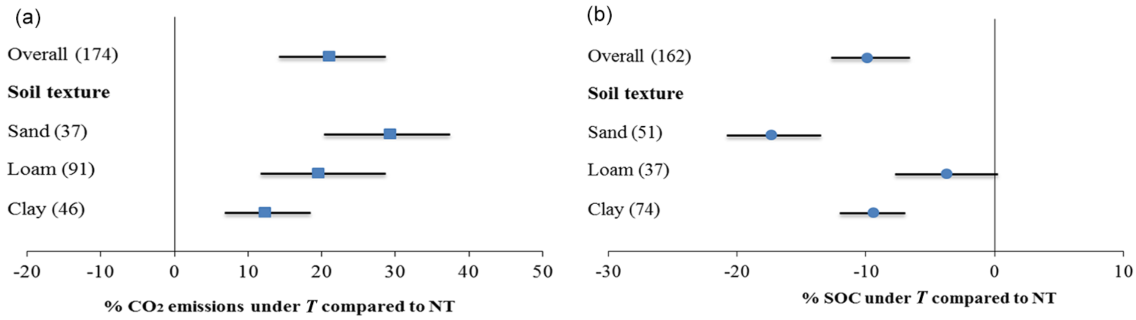

Figure 3. Percent change in **(a)** soil CO_2 emissions and **(b)** SOC in tillage (T) soil compared to no-tillage (NT) as a function of soil particle distribution (clay, loam and sand). The numbers in the parentheses indicate the direct comparisons of the meta-analysis. Error bars are 95 % confidence intervals.

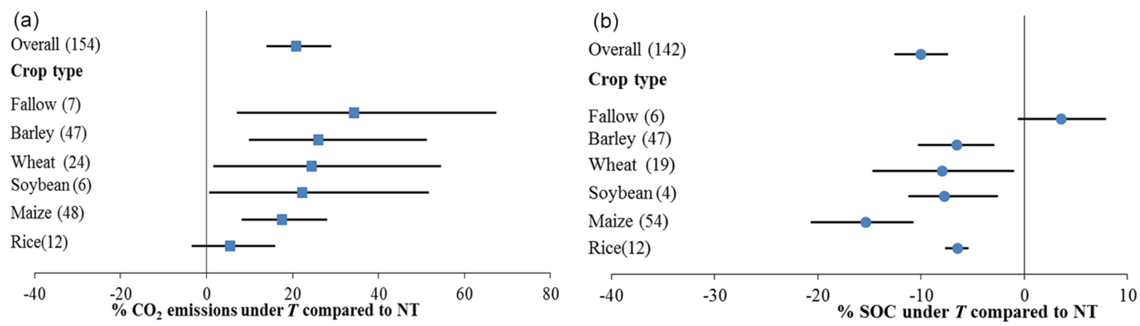

Figure 4. Percent change in **(a)** soil CO_2 emissions and **(b)** SOC in tillage (T) soil compared to no-tillage (NT) as a function of crop type. The numbers in the parentheses indicate the direct comparisons of meta-analysis. Error bars are 95 % confidence intervals.

tilled and untilled soils were observed for maize where SOC_C was on average 15 % lower under tillage compared to no-tillage.

3.2.5 Duration of no-tillage

The duration of no-tillage (i.e. time since tillage was abandoned) had no statistical association with soil CO_2 emissions. However, there was a tendency for the differences between tillage and no-tillage to increase with increasing duration of the no-tillage regime with an average 18 % difference for experiments of less than 10 years, and 23 % for those longer than 10 years (Fig. 5a). SOC_C under tillage was 14 % lower compared to no-tillage for experiments lasting longer than 10 years, whereas there were no differences in SOC_C between tillage and no-tillage for shorter durations (Fig. 5b).

3.2.6 Nitrogen fertilization

Nitrogen fertilization did not produce statistically significant differences between soil CO_2 emissions and SOC_C differences from tilled and untilled soil (Fig. 6). Compared to tillage, no-tillage decreased soil CO_2 emissions by an average of 19 % when 100 kg N ha^{-1} or more was applied, while at lower fertilization rates, soil CO_2 emissions decreased by 23 %, but owing to the small sample size this difference was not statistically significant.

3.2.7 Crop residue management and crop rotation

On average, when crop residues were not exported, no-tillage decreased soil CO_2 emissions by 23 % compared to tillage, which corresponded to a significant difference at $P < 0.05$. On the other hand, crop residue removal resulted in a smaller difference of only 18 % (Fig. 7a). SOC_C was 12 % lower under tillage than no-tillage in the absence of crop residues, and only 5 % lower when crop residues were left on the soil (Fig. 7a). On the other hand, soils under a crop rotation regime exhibited much sharper decrease (i.e. 26 %) of CO_2 emission following tillage abandonment than the soils under continuous monoculture for which changes of CO_2 emission were not significant at $P < 0.05$.

3.2.8 Multiple correlations between soil CO_2 emissions and selected soil variable and environmental factors

Figure 9 shows the interaction between the changes in CO_2 emissions following tillage abandonment on one hand and the selected soil and environmental variables on the other. The first two axes of the PCA explained 66 % of the entire

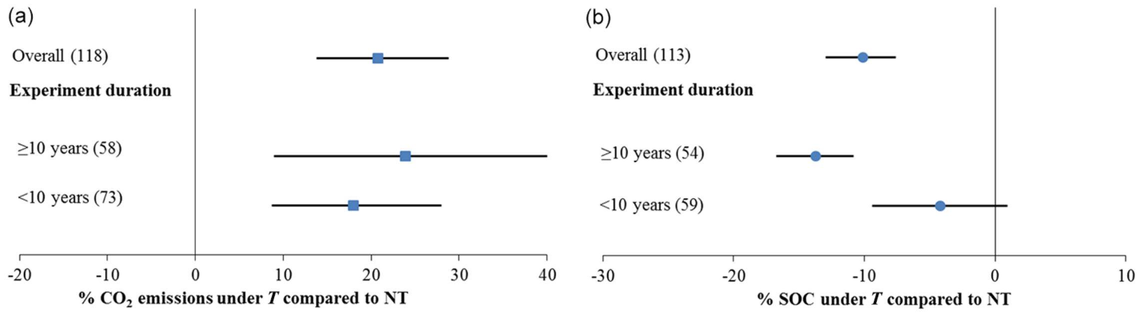

Figure 5. Percent change in **(a)** soil CO_2 emissions and **(b)** SOC in tillage (T) soil compared to no-tillage (NT) as a function of experiment duration (< 10 years and ≥ 10 years). The numbers in the parentheses indicate the direct comparisons of the meta-analysis. Error bars are 95 % confidence intervals.

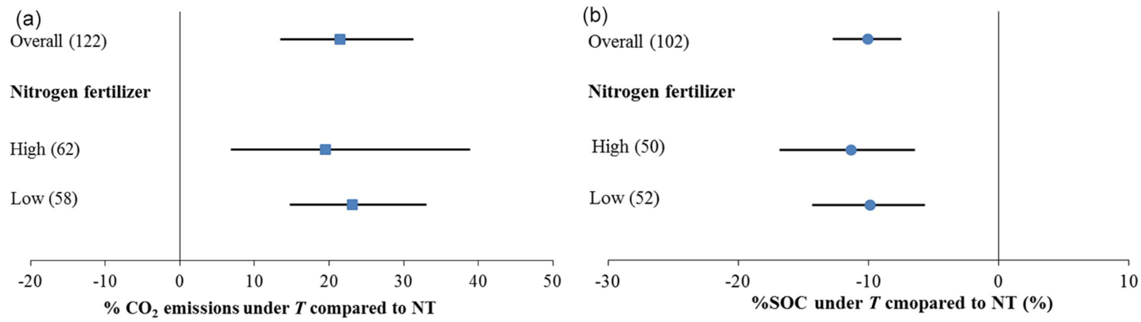

Figure 6. Percent change in **(a)** soil CO_2 emissions **(b)** and SOC in tillage (T) soil compared to no-tillage (NT) as a function of nitrogen fertilization (low < 100 kg N ha^{-1} and high ≥ 100 kg N ha^{-1}). The numbers in the parentheses indicate the direct comparisons of the meta-analysis. Error bars are 95 % confidence intervals.

data variability. The first PCA axis (Axis 1), which described 35 % of the total data variance, was highly correlated to latitude (LAT), mean annual temperature (MAT), SOCc, and soil clay content (CLAY). LAT and ρb showed positive coordinates on Axis 1, while the other variables showed negative ones. Axis 1 could, therefore, be regarded as an axis, setting clayey organic and warm soils against compacted, sandy soils from a cold climate. The second PCA axis, which explained 21 % of the data variance, correlated the most with silt content. The differences in CO_2 fluxes between tillage and no-tillage ($\Delta CO_{2T-\mathrm{NT}}$) showed positive coordinates on Axis 1, which revealed greater CO_2 emissions under tillage compared to no-tillage under cool sandy and dense soils compared to warm clayey and organically rich soil from a warm and humid climate.

4 Discussion

4.1 Overall influence of tillage on SOC_C and soil CO_2 emissions

Our meta-analysis shows that tillage has a significant impact on decreasing topsoil (0–0.03 m) organic carbon content (SOC_C) and increasing CO_2 emissions, with 10 % lower SOC_C and 21 % greater CO_2 emission in tilled than untilled soils. Lower SOC_C and greater CO_2 emissions under tillage reflect faster organic matter decomposition as a result of greater soil aeration and incorporation of crop residues to the soil, and breakdown of soil aggregates, which all render the organic material more accessible to decomposers (Reicosky, 1997; Six et al., 2002, 2004). However, results from the literature do not always agree with this. In case of soil carbon, for example, Cheng-Fang et al. (2012) found 7–48 % greater SOC_C under tilled rice in China, when Ahmad et al. (2009) observed no significant differences. In case of soil CO_2 emissions, while for instance Ussiri and Lal (2009) for a 43 years maize monoculture in USA observed 31 % greater CO_2 emissions from tilled than from no-tilled soils, Curtin et al. (2000) and Li et al. (2010) found no significant difference in CO_2 emissions between these treatments while Oorts et al. (2007) reported greater soil CO_2 emission under no-tillage (4064 kg CO_2-C ha^{-1}) compared to tillage (3160 kg CO_2-C ha^{-1}), which they attributed to greater soil moisture content and amount of crop residue on the soil surface.

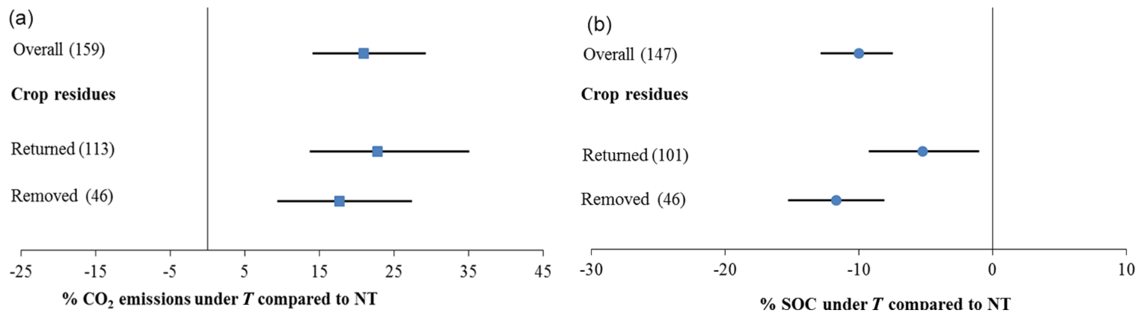

Figure 7. Percent change in **(a)** soil CO_2 emissions and **(b)** SOC in tillage (T) soil compared to no-tillage (NT) as a function of crop residues (returned and removed). The numbers in the parentheses indicate the direct comparisons of the meta-analysis. Error bars are 95 % confidence intervals.

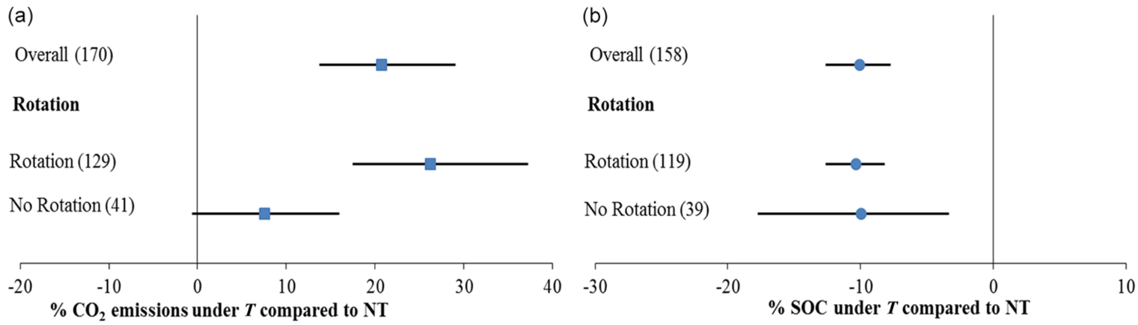

Figure 8. Percent change in **(a)** soil CO_2 emissions and **(b)** SOC in tillage (T) soil compared to no-tillage (NT) as a function of crop rotation. The numbers in the parentheses indicate the direct comparisons of the meta-analysis. Error bars are 95 % confidence intervals.

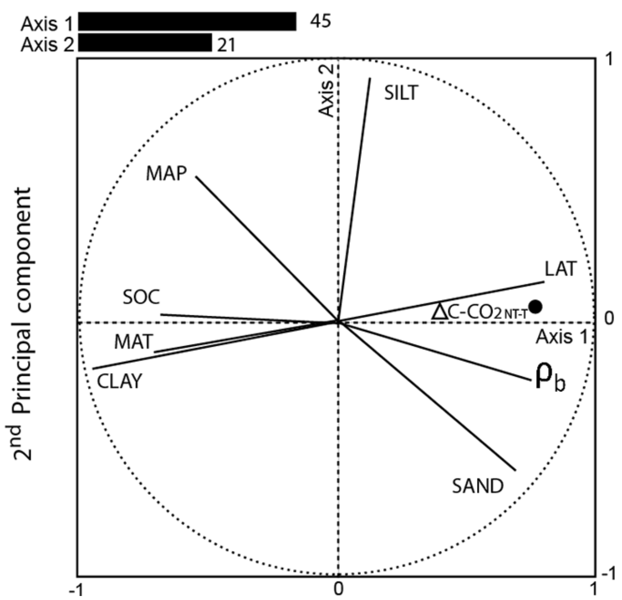

Figure 9. Principal components analysis (PCA) using the different environmental factors as active variables and soil CO_2 emission difference between T and NT ($\Delta CO_{2T-\mathrm{NT}}$) as the supplementary variable.

4.2 Influence of climate

Although there was no significant difference between arid and humid climates, CO_2 emissions and SOC_C changes between untilled and tilled soils tended to be greater in arid than in humid climates (Fig. 1a). In support, Álvaro-Fuentes et al. (2008), who investigated tillage impact on CO_2 emissions from soils in a semiarid climate, attributed the observed large difference between tillage and no-tillage to differences in soil water availability. At humid sites high soil moisture favour high decomposition rates resulting in small differences between tilled and untilled soils, while large differences develop in arid climates with much lower soil water content (Fortin et al., 1996; Feizienė et al., 2011). This supports the idea that the soil response to tillage is affected by climate thresholds (Franzluebbers and Arshad, 1996).

4.3 Influence of soil properties

4.3.1 Soil organic carbon content

The decrease of CO_2 emission differences between tillage and no-tillage with increasing SOC_C is most likely due to diminishing inter-aggregate protection sites as SOCc level increases. Several studies have shown that carbon inputs into carbon-rich soils show little or no increase in soil carbon content with most of the added carbon being released to the atmosphere, while carbon inputs in carbon-depleted soils translate to greater carbon stocks because of processes that stabilize organic matter (Paustian et al., 1997; Solberg et al., 1997; Six et al., 2002). Another reason, which does not involve stabilization, is the fact that soils that have been depleted in carbon tend to recover and accumulate SOC until equilibrium is reached (Carvalhais et al., 2008). Therefore, abandoning tillage in soils with low SOC_C tends to offer greater protection of SOC than in soils with inherently high SOC_C levels. In support, Lal (1997) reported low SOC_C and aggregation correlations under high SOC_C soils, which suggests that substantial proportions of the SOC were not involved in aggregation. Hence, the greater difference of CO_2 emissions between tilled and untilled soils for carbon-depleted soils compared to carbon-rich soils may be due to much greater stabilization of extra SOC delivered to the carbon-depleted soil by protection in soil aggregates within the topsoil layers (0.0–0.05 m). Tillage of carbon-depleted soils is likely to lead to the breakdown of more soil aggregates, thus leading to greater decomposition of the residues added under no-tillage, as hypothesized by Madari et al. (2005) and Powlson et al. (2014).

4.3.2 Soil texture

Soils under zero tillage emitted less CO_2 than tilled soils, and the CO_2 emission difference was the greatest in sandy soils (Fig. 3). Further, in sandy soils, as indicated by Fig. 3, the largest CO_2 emission difference is mirrored by the largest SOC_C difference.

Greater SOC_C and then CO_2 differences under sandy soils might be due to the lower resistance of soil aggregates to disaggregation, with tillage accelerating aggregate breakdown and decreasing organic matter protection, which causes a fast loss of soil carbon. Differences in CO_2 emissions between treatments were greater in sandy than in clayey soils (Fig. 3). This might be due to the fact that sandy soils have higher porosity, allowing changes in soil management to translate into large variations in the gas fluxes to the atmosphere (Rastogi et al., 2002; Bauer et al., 2006). These suggestions contrast, however, with the results of, for instance, Chivenge et al. (2007) working in Zimbabwe and in other locations where little impact of tillage on carbon sequestration was found under sandy soils as compared to clayey ones.

4.4 Influence of the duration since tillage abandonment

The differences in SOC_C between tilled and untilled soils increased with the time since abandonment of tillage (Fig. 5b). When abandonment of tillage took place before less than 10 years, there were no differences in SOC_C between tillage and no-tillage, but for longer durations, tilled soils had 14 % less SOC_C than untilled soils. This can be explained by the progressive increase of soil carbon accumulation with time as a result of the retention of a fraction of the crop residue under no-tillage. This explanation is consistent with the results of Paustian et al. (1997) and Ussiri and Lal (2009). Six et al. (2004) reported that the potential of no-tillage to mitigate global warming is only noticeable a long time after (> 10 years) a no-tillage regime has been adopted. This would suggest that shifts in CO_2 emission differences between tillage and no-tillage will occur over time; this could not be observed in our analysis (Fig. 5a) because the majority of experiments in this study were less than 10 years in length. Further, in some cases no-tillage leads to carbon loss in the topsoil layer (0–0.3 m) during the first years of adoption (Halvorson et al., 2002; Six et al., 2004), a response which can be attributed to slower incorporation of surface residues into the soils by soil fauna. However, different studies give contrasting results; for instance, the long-term no-tillage experiments in northern France by Dimassi et al. (2014) showed that SOC increased in the topsoil (0–0.1 m) during 24 years after tillage abandonment, then did not increase, whereas SOC continuously decreased below 0.1 m. A loss of SOC following tillage abandonment was also suggested by Luo et al. (2010) and Baker et al. (2007).

4.5 Crop types, residue management, and crop rotation

The no-tillage minus tillage variations of CO_2 emission and SOC_C between crop types are correlated with the quantity and quality of crop residue (Fig. 4a–b). Both quantity and quality of crop residues are important factors for soil carbon sequestration and CO_2 emissions, and are highly dependent on crop type. Reicosky et al. (1995), reported that corn returned nearly twice as much residue than soybean, and that soybean residues decomposed faster because of their lower C : N ratio. Thus, maize residues result in higher soil organic matter than soybean. Al-Kaisi and Yin (2005) also reported reduced soil CO_2 emissions and improved soil carbon sequestration in maize-soybean rotations due to better residue retention. Reicosky (1997) summarized that maximizing residue retention results in carbon sequestration with subsequent decrease in CO_2 emissions. However, several recent studies pointed to the lack of impact of residue management on soil carbon, with Lemke et al. (2010) showing that crop-residue removal in a 50-year experiment did not significantly ($P > 0.05$) reduce soil carbon, and Ren et al. (2014) showing that inputs from wheat straw and manure up to 22 ton ha^{-1} yr^{-1} could not increase soil carbon over 4 years. De Luca et al. (2008) explained the lack of crop residue impact on soil carbon with the very low amount of carbon in residues compared to the bulk soil in their study, while Russell et al. (2009), having investigated several systems, pointed out to a concomitant increase of organic matter decomposition with carbon input rates.

Wilson and Al Kazi (2008) indicated that continuous corn cropping systems had higher soil CO_2 emissions than corn-soybean rotations because of a greater residue amount. Van

Eerd et al. (2014) concluded from winter that wheat–legumes rotations yielded higher carbon input during wheat cultivation, due to a greater belowground allocation. The present analysis suggests that tilled soils have significantly greater CO_2 emissions than no-tilled soils irrespective of the crop rotation system (Fig. 8). This is likely because crop rotation increases SOC_C, microbial activity, and diversity. For instance, Lupwayi et al. (1998, 1999) found greater soil microbial biomass under tillage legume-based crop rotations than under no-tillage with tillage increasing the richness and diversity of active soil bacteria by increasing the rate of diffusion of O_2 and the availability of energy sources (Pastorelli et al., 2013). This study showed that continuous monoculture did not result in significantly different CO_2 between tilled and untilled soils (Fig. 8a). Rice is one crop often produced under a continuous monoculture practice; however, in this meta-analysis, paddy rice did not show significant difference of CO_2 emissions between tillage and no-tillage. Li et al. (2010) and Pandey et al. (2012) attributed the lack of difference to anaerobic soil conditions occurring under both practices.

4.6 Nitrogen fertilization

The differences of CO_2 between tillage and no-tillage did not differ with nitrogen fertilizer level (Fig. 6a), confirming observations by Alluvione et al. (2009) and Almaraz et al. (2009b). This result could be due to the fact that nitrogen fertilization increases productivity and carbon inputs to the soil under both tilled and untilled systems, which may override nitrogen effects on decomposition such as shown by Russell et al. (2009). Increasing SOC as a response to nitrogen fertilization was found under no-tillage during a period of 4 years (Morell et al., 2010), and during the 50 year experiment of Lemke et al. (2010). Yet Sainju et al. (2008) reported the opposite: a 14 % increase of soil CO_2 flux with nitrogen fertilizer, because fertilizer application stimulated biological activity, thereby producing more CO_2, and causing SOC_C decline (Khan et al., 2007; Mulvaney et al., 2009). In contrast, Wilson and Al Kazi (2008) showed that increasing N fertilization generally decreased soil CO_2 emissions, with a maximum decrease of 23 % from 0–135 $kg\,N\,ha^{-1}$ to 270 $kg\,N\,ha^{-1}$ occurring during the growing season, which might be explained by a series of mechanisms, including the inhibition of soil enzymes and fungus and the reduction of root activity.

Overall, these results pointed to little benefit in not tilling clayey soils with high SOC_C, with the highest no-tillage benefits occurring under sandy soils with low SOC_C. This can be explained by differences in soil aggregate stability. Indeed, since the stability of soil aggregates shows a positive correlation with clay and organic matter content, clayey and organic soils produce stable aggregates which are likely to be more disaggregated by tillage compared to sandy aggregates of low carbon content. The SOC protected within soil aggregates under no-tillage becomes exposed under tillage because of aggregate dispersion; which explains the greater reduction in CO_2 emission with no-tillage under sandy soils. Rather, emission is likely to be reduced under zero tillage as a result of improved soil aggregate stability and the associated protection of decomposed and stable organic matter. Crop management such as fertilization and crop type, or climate are shown to have little effect on aggregation. Our analysis did not include time since cessation of tillage as a specific predictor and classified instead the experiments into two simple categories (short vs. long term).

5 Conclusion

The aim of this study was to provide a comprehensive quantitative synthesis of the impact of tillage on CO_2 emissions using meta-analysis. Three main conclusions can be drawn. Firstly, tillage systems had 21 % greater CO_2 emissions than no-tillage, worldwide. Secondly, the reduction in CO_2 emissions following tillage abandonment was greater in sandy soils with low SOC_C compared to clayey soils with high SOC_C. Thirdly, crop rotation significantly reduced the CO_2 emissions from untilled soil, by 26 % compared to tilled soil, while continuous monocultural practice had no significant effect. This is most probably due to the fact that crop rotation can increase SOC_C and more microbial activity under a tilled compared to an untilled treatment. These results emphasize the importance of including soil factors such as texture, aggregate stability and organic carbon content in global models of the carbon cycle.

Long-term process studies of the entire soil profile are needed to better quantify the changes in SOC following tillage abandonment and to clarify the changes in the dynamics of carbon inputs and outputs in relation to changes in microbial activity, soil structure and microclimate. In addition, more research is needed to identify the underlying reasons why, over a long period of time, the abandonment of tillage results in a decrease in integrated CO_2 emissions, that appears to be much higher than the observed increase in SOC_S. The goal remains to design agricultural practices that are effective at sequestering carbon in soils.

Finally, one future application of these data could be to use them to calibrate soil carbon models. The models could be run with prescribed inputs (from observation sites) used to simulate decomposition and the mass balance of SOC over time for different climates, soil texture and initial SOC content with respect to the theoretical value assuming equilibrium of decomposition and input (Kirk and Bellamy, 2010). Most soil carbon models developed for generic applications (e.g. RothC, DNDC, and CENTURY) would be suitable tools for exploitation of the data presented here (Adams et al., 2011).

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