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Greenhouse gas emissions and crop yield in no-tillage systems: A meta-analysis

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ABSTRACT

No-tillage (NT) has been touted as one of several climate-smart agriculture (CSA) management practices that improve food security and enhance agroecosystem resilience to climate change. However, the sustainable effectiveness of NT greatly depends on trade-offs between NT-induced changes in crop yield and greenhouse gas (GHG, i.e. CH_4, CO_2, and N_2O) emissions. Such trade-offs are regulated by climate fluctuations and heterogeneous soil conditions and have not been well addressed. Supporting CSA management decisions requires advancing our understanding of how NT affects crop yield and GHG emissions in different agroecological regions. In this study, a meta-analysis was conducted using 740 paired measurements from 90 peer-reviewed articles to assess the effects of NT on crop yield, GHG emissions, and the global warming potential (GWP) of major cereal cropping systems. Compared to conventional tillage (CT), NT reduced in GHG emissions and increased crop yield in dry, but not humid, climates, and reduced in the GWP at sites with acidic soils. Across different cropping systems, NT enhanced barley yield by 49%, particularly in dry climates, and it decreased the GWP of rice fields through a 22% reduction in both CO_2 and CH_4 emissions. Our synthesis suggests that NT is an effective CSA management practice because of its potential for climate change mitigation and crop yield improvement. However, the net effect of NT (relative to CT) was influenced by several environmental and agronomic factors (climatic conditions, tillage duration, soil texture, pH, crop species). Therefore, agroecological setting must be taken into consideration when conducting a comparative evaluation of different tillage practices.

1. Introduction

Among all anthropogenic sources, agriculture is estimated to be responsible for 12% of total greenhouse gas (GHG) emissions (IPCC, 2014), particularly global anthropogenic CH_4 (39%) and N_2O (76%) emissions (FAO, 2014; WRI, 2014). With increasing demands on agriculture to feed a growing world population, GHG emissions from agroecosystems will likely continue to rise. Climate-smart agriculture (CSA) focuses on methods to maintain or increase food production while simultaneously reducing agriculture's GHG emissions and other environmental side effects under various climate scenarios (FAO, 2013). No-tillage (NT) management has been proposed as a component of CSA (Lipper et al., 2014). In NT, crop residues are left on the soil surface and only in-row soil is disturbed during seeding (Dinnes, 2004). Compared to conventional tillage (CT), NT exhibits greater potential for soil carbon sequestration, soil quality improvement, and sustained crop productivity (Lal et al., 2007; Lal, 2015; Abdalla et al., 2016). No-tillage was practiced on approximately 111 million ha worldwide in 2009 (Derpsch et al., 2010), and this number reached 155 million ha in 2014 (FAO, 2014). One may reasonably speculate that NT management can potentially have global scale impact on the magnitude and spatial patterns of soil GHG emissions and crop production (Fig. 1). However, from a sustainability perspective, the net effect of NT greatly depends on the trade-offs between NT-induced changes in crop yield and GHG emissions. These trade-offs are regulated by a suite of climatic and soil factors, which have not been well addressed in past studies.

The precise effects of NT on soil GHG emissions remain controversial and greatly vary among past studies (Van Kessel et al., 2013;

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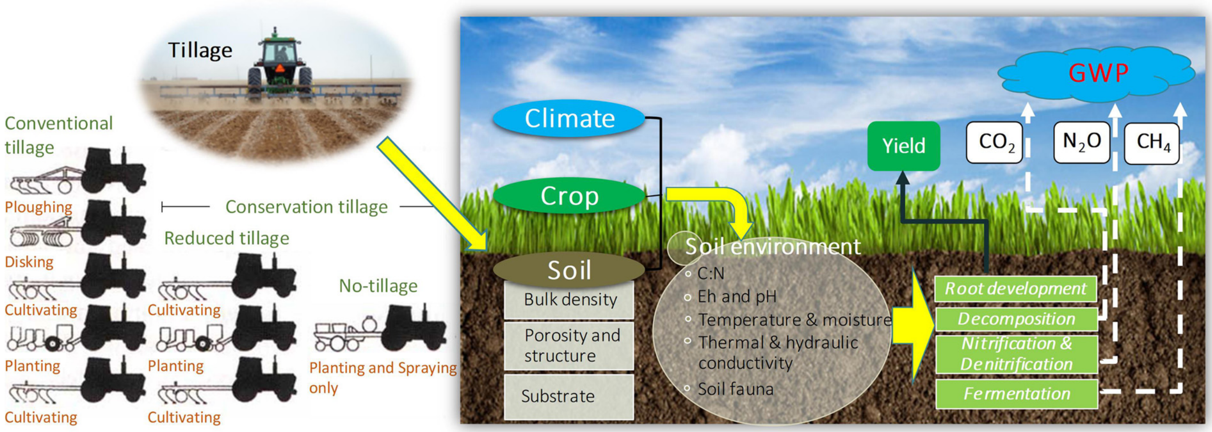

Fig. 1. Conceptual framework of diverse tillage practices impact on soil processes (biophysical, biophysiological, and biogeochemical), greenhouse gas (GHG) emissions, and crop yields.

Zhao et al., 2016). Some studies showed a substantial decrease in soil CO_2, CH_4, and N_2O emissions with NT (e.g., Li et al., 2011; Drury et al., 2012; Lu et al., 2016), while others reported a significant increase or no difference (e.g., Oorts et al., 2007; Yao et al., 2013; Zhang et al., 2016b). For example, a long-term study in a Mediterranean dryland agroecosystem exhibited a 50% increase in CO_2 emission but no difference in N_2O emission in NT compared to CT (Plaza-Bonilla et al., 2014a,b). Kim et al. (2016) reported that total CH_4 flux from NT rice fields decreased by 20–27% in the first and second years after NT imposition, but it was approximately 36% higher than that from CT fields by the fifth year. Zhang et al. (2016a) also observed a substantial decline in CH_4 and CO_2 emissions from NT rice fields compared to CT fields. Another rice field experiment exhibited significant CO_2 emission reduction but increased N_2O emission in NT (Fangueiro et al., 2017). Therefore, the climate change mitigation efficacy of NT is still uncertain.

Several hypotheses have been proposed to explain the different soil GHG emission responses due to NT. For example, a decrease in soil CO_2 emission in NT might be due to carbon protection associated with enhanced soil aggregation and decreased soil temperature (He et al., 2011; Lu et al., 2016), while an acceleration in soil CO_2 emission might be due to enhanced microbial activity caused by greater soil moisture availability (Plaza-Bonilla et al., 2014b). Elevated CH_4 emission could be attributed to greater abundance of organic substrates and coincident formation of anaerobic microsites (Zhang et al., 2015). Reduced CH_4 emission might be associated with improved soil porosity and gas diffusivity, facilitating the transport of CH_4 to methanotrophs (Ball et al., 1997; Prajapati and Jacinthe, 2014). NT-induced increases in soil carbon and water content (and therefore higher water-filled pore space) could favor denitrification, ultimately resulting in elevated soil N_2O emission (Ma et al., 2013; Sheehy et al., 2013). In contrast, factors that may contribute to decreased N_2O emission include improved soil structure, lower soil temperature, a limited pool of decomposable organic carbon and low availability of mineral nitrogen due to a slow rate of soil organic matter (SOM) mineralization (Grandy et al., 2006; Chatskikh and Olesen, 2007; Ruan and Robertson, 2013).

With regard to the response of crop productivity to NT, there is also little consensus from the literature (FAO, 2011; Pittelkow et al., 2015). Some studies concluded that crop yield in water-limited conditions often increases with NT adoption (Farooq et al., 2011; Rusinamhodzi et al., 2011). Other studies reported decreased crop productivity in NT due to cooler soil temperatures, soil compaction, and altered soil fertility requirements (e.g., micronutrient deficiencies; Ogle et al., 2012).

These contradictory reports suggest that NT effects may be regulated by many variables, including environment (e.g., climate and soil properties) and management (e.g., crop type, fertilization, tillage duration) factors (Daryanto et al., 2017a). These factors may determine the extent to which NT affects the soil carbon and nitrogen cycles and, consequently, soil GHG emissions and crop productivity. Climate, in particular, influences the frequency and amount of precipitation, soil moisture regime, and the production of soil GHGs. Several recent meta-analyses have synthesized data on GHG emissions and crop yield, but these syntheses focused largely on either one GHG species, a specific cropping system, or a specific geographical region. For example, Abdalla et al. (2016) examined CO_2 emission in response to NT, and van Kessel et al. (2013) emphasized the central tendency of N_2O emission and the decreasing crop yield trend in NT. While Zhao et al. (2016) assessed N_2O and CH_4 emissions in response to NT, their study was restricted to China. Pittelkow et al. (2015) evaluated the influence of crop species and environmental variables on NT and CT crop yields, but they did not account for soil GHG emissions. Assessing the efficacy of NT as a CSA practice requires a simultaneous examination of NT impacts on crop productivity and GHG emissions across different crops and climatic regions.

In light of interest in NT as a CSA practice, and uncertainties associated with NT impacts, we conducted a meta-analysis to simultaneously evaluate NT effects on soil GHG (i.e. CH_4, CO_2, and N_2O) emissions and crop yield. Specifically, we focused on four major cereal crops (barley, maize, rice, and wheat) which, combined, contribute more than half of all calories consumed by humans and cover more than 45% of global cropland (FAO, 2014). Our objectives were to: (1) examine soil GHG emissions and crop yield with NT soil management in various environmental and management conditions; (2) identify factors contributing to food security and climate change mitigation in support of NT as an effective CSA management practice.

2. Materials and methods

2.1. Data compilation

The data in this meta-analysis were collected from peer-reviewed publications reporting *in situ* soil GHG emissions and crop yield in both CT and NT soil management. A literature survey was performed using the Web of Science and Google Scholar (1900–2017). Key words used for the initial search included "tillage," "greenhouse gases," "CO_2," "CH_4,", and "N_2O." The literature survey focused on GHG emissions from four cereal crops (barley, maize, rice, and wheat). Three criteria were considered to minimize bias and ensure database quality when selecting studies. First, GHG emissions were measured *in situ* for the entire cropping season. Second, the CT versus NT comparison was done under otherwise similar agronomic management practices. Third, information regarding means, standard deviations (or standard errors),

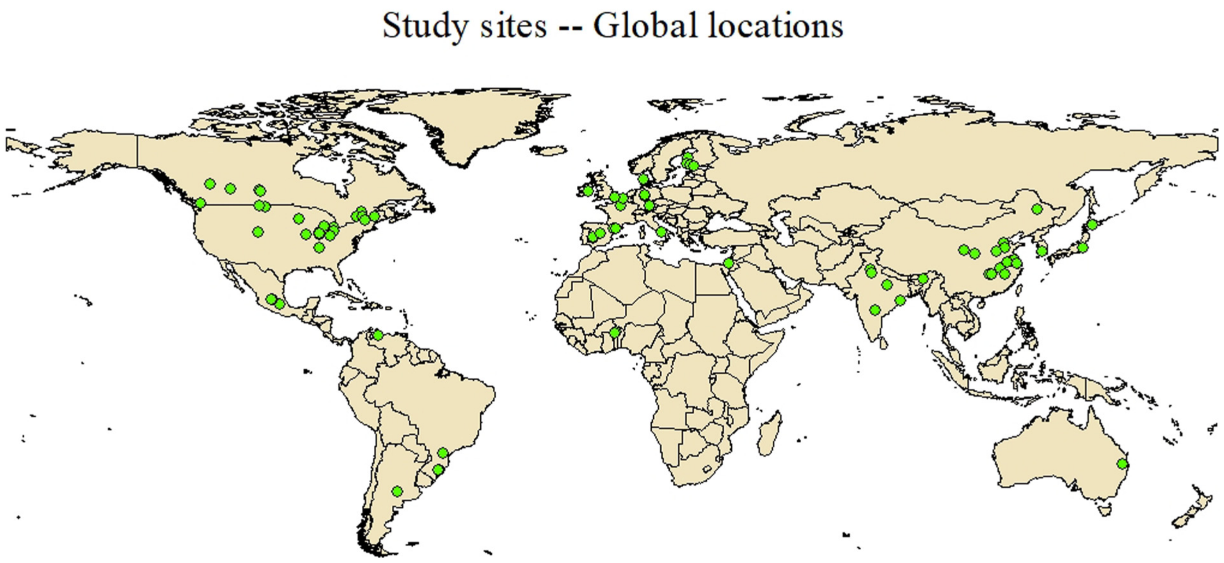

Fig. 2. Global distribution of the study sites.

replications, and the magnitude of seasonal cumulative GHG emissions was either available or could be calculated.

Based on these criteria, 90 peer-reviewed articles with 139 comparisons for CO_2 emission, 65 for CH_4 emission, 56 for CH_4 uptake, 299 for N_2O emission, and 181 for crop yield were collected for the meta-analysis (Data S1). These studies came from 20 different countries (Fig. 2). The GHG and crop yield data were either derived from tables or extracted from figures using WebPlotDigitizer (Rohatgi, 2012). Other related information, including location (longitude and latitude), mean annual temperature (MAT), mean annual precipitation (MAP), land use, duration of the experiment, soil type, soil pH, crop residue management, and the rate and placement of N fertilizer inputs was recorded. To disentangle the effects of other co-varying factors on GHG emissions and crop yield, data were further analyzed with two major categorical variables (i.e. environment and management), except when data availability constraints existed (Table 1). Climate regions were classified using global aridity values according to a generalized climate classification scheme (UNEP, 1997). The aridity index of each study site was extracted from the WorldClim database (Hijmans et al., 2005). Study sites with an aridity index > 0.65 were considered "humid" whereas study areas with a lower index (< 0.65) were grouped as "dry." Soil pH was classified into three categories following Havlin et al. (2013): acidic (pH < 6.6), neutral (6.6 ≤ pH ≤ 7.3), and alkaline (pH > 7.3). Soil texture was classified according to the USDA soil texture triangle. Clay, sandy clay, and silty clay classes were designated "fine textured;" silt, silt loam, silty clay loam, loam, sandy clay loam, and clay loam were considered "medium textured;" and sand, loamy sand, and sandy loam were grouped as "coarse textured" (Daryanto et al., 2017a,b). Nitrogen (N) fertilization rates were grouped into four categories: control (no fertilizer applied), low (less than 100 kg N $ha^{-1}yr^{-1}$), medium (between 100 and 200 kg N $ha^{-1}yr^{-1}$), and high (greater than 200 kg N $ha^{-1}yr^{-1}$). Fertilizer N placement was grouped into "surface application" and "subsurface application." Methods such as injection, drilling, and side-dressing (depths of placement were clearly described in the literature) were considered to be subsurface N fertilizer applications. Crop residue management was classified as either "removed" or "retained." No-tillage management duration was determined according to NT establishment in each experiment. The NT treatment was considered "short" duration when imposed for less than 5 years, "medium" duration when present for 5 to 10 years, and "long" duration when exceeding 10 years.

Table 1
Categories used in describing the environmental and management conditions.

Factors	Categories			
Environmental factors				
Climate	Dry	Humid		
Soil texture	Fine	Medium	Coarse	
Soil pH	Acid (< 6.6)	Neutral (6.6–7.3)	Alkaline (> 7.3)	
Management practices				
Crop type	Rice	Wheat	Maize	Barley
Tillage duration	< 5 years	5–10 years	≥ 10 years	
N fertilizer	Control (0)	Low (< 100 kg N $ha^{-1}yr^{-1}$)	Medium (100–200 kg N $ha^{-1}yr^{-1}$)	High (≥ 200 kg N $ha^{-1}yr^{-1}$)
N placement	Surface (SUR)	Subsurface (SUB)		
Crop residue management	Removed (RM)	Retained (RT)		

The variation in observed emission and yield was recorded and converted to standard deviation (SD). The SD values were computed from standard error (SE) by the equation: $SD = SE \times \sqrt{n}$, where n is the number of replications. When SD and SE were missing, SD was estimated from the average coefficient of variation for the known data (Zhao et al., 2016).

2.2. Data analysis

Meta-analysis combines and compares results from pertinent independent studies by weighting these results according to their differences in precision. A random-effect meta-analysis was performed to explore environmental and management variables that might explain the response of GHG emissions and crop yield to NT. In this meta-analysis, response ratios (R) comparing NT and CT, for GHG emissions and crop yield, were calculated as follows:

$$R = \left(\frac{X_{NT}}{X_{CT}}\right) \tag{1}$$

where X is the variate (CO_2, CH_4, N_2O, GWP, or crop yield) mean, for either the NT or the CT treatment. The natural logarithm of R (lnR), the effect size, was calculated for each treatment in every trial/experiment (Hedges et al., 1999; Deng et al., 2017). The variance (υ) of lnR was computed as:

$$\upsilon = \frac{SD_{NT}^2}{n_{NT}X_{NT}^2} + \frac{SD_{CT}^2}{n_{CT}X_{CT}^2} \tag{2}$$

where SD and n are standard deviation and sample sizes, respectively, either in CT or NT. The weight of each effect size was:

$$\omega = \frac{1}{v} \tag{3}$$

The mean effect sizes were estimated as:

$$\overline{lnR} = \frac{\sum (lnR_i \times \omega_i)}{\sum \omega_i} \tag{4}$$

where lnR_i and ω_i were the effect size and weight from the ith comparison, respectively. The 95% confidence interval (CI) of $\overline{lnR}$ was computed as:

$$95\%CI = \overline{lnR} \pm 1.96SE_{\overline{lnR}} \tag{5}$$

where $SE_{\overline{lnR}}$ is the standard error of $\overline{lnR}$ and was computed as:

$$SE_{\overline{lnR}} = \sqrt{1/\sum \omega_i} \tag{6}$$

SAS software was used to analyze the data by applying the macros for meta-analysis procedure (Lipsey and Wilson, 2001). The effect size means were significantly different if their 95% CI do not overlap with zero. The percent change in selected variables was computed using the equation:

$$\left(e^{\overline{lnR}} - 1\right) \times 100\% \tag{7}$$

Global warming potential was calculated when fluxes for all three GHG species (i.e. CH_4, CO_2, and N_2O) were reported in each single study. The units of soil CH_4, and N_2O fluxes were converted into CO_2-equivalent units before GWP calculation. We used the IPCC factors (IPCC, 2013) to calculate GWP in CO_2-equivalents ha^{-1} yr^{-1} over a 100-year time horizon:

$$GWP = CO_2 \times 1 + CH_4 \times 34 + N_2O \times 298 \tag{8}$$

Each categorical environment and management variable was treated as a moderator in analyzing the whole dataset. The Chi-square test was then used to calculate the between-group heterogeneity for a given variable across all the data to further analyze the NT effect for different sub-categories. Publication bias was tested by the funnel plot method and assessed using Kendell's rank correlation (Begg and Mazumdar, 1994). If the mean effect exhibited a significant difference from zero (i.e. indicating publication bias), Rosenthal's fail-safe or file drawer number was calculated (METAFOR package in R) to estimate if our conclusion was likely affected by nonpublished studies (Rosenberg, 2005).

3. Results

3.1. Overall effects of NT on GHG emissions and crop yield

On average, CO_2 emission rate was not significantly different between NT and CT (CI overlapped with zero; Fig. 3). In contrast, NT significantly increased N_2O emission by 10.4% with a mean weighted $\overline{lnR}$ of 0.10 [CI = (0.02, 0.17)] (Fig. 3). For locations exhibiting net CH_4 uptake, we found no difference between NT and CT. Whereas for sites with net CH_4 emission, NT reduced CH_4 emission by 15.5%, with an $\overline{lnR}$ of -0.17 [CI = (-0.30, -0.03)] (Fig. 3). Therefore, a reduction in CH_4 emission was the major contribution of NT management to GHG mitigation. Crop yields were similar between NT and CT (CI overlapped with zero, Fig. 3), suggesting that yield loss should not be a deterrent to NT adoption as a CSA practice. Publication bias for CH_4 uptake analysis was suggested by Rosenthal's fail-safe number method, but it was not found for the other variables (Table S1).

Our analysis revealed several environment and management variables affecting GHG emissions and crop yield in NT (versus CT) management. The response of soil CO_2 emission to NT varied significantly with crop species, climate regime, NT duration, soil pH, and crop residue management. No-tillage-induced changes in CH_4 flux were significantly influenced by crop species, soil pH, and NT duration. No-tillage-induced changes in N_2O flux were significantly impacted by N fertilizer placement. Differences in crop yield due to NT were significantly related to crop species, climate, and both N fertilizer rate and placement (Table 2).

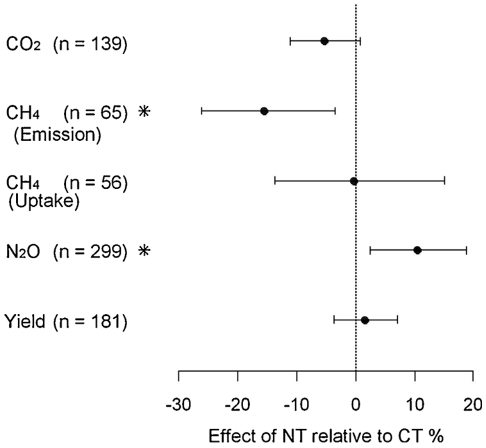

Fig. 3. Overall changes in soil greenhouse gas (GHG) emissions and crop yields between NT and CT. Numerals indicate the number of observations. * represents $p < 0.05$.

3.2. Effects of environment on NT vs. CT comparison

3.2.1. Climate

Compared to CT, NT significantly decreased CO_2 emission (-9.9%) in dry climates, but not in humid climates (Fig. 4a). However, significant reductions in soil CH_4 emission (-18.9%) with NT occurred in humid climates (Fig. 4b). Similarly, NT increased soil CH_4 uptake (47%) in humid climates (Fig. S1a). Although climate did not significantly affect the difference in N_2O emission between the tillage practices (Table 2), N_2O emission in NT was greater (12.3%) than in CT for humid climates (Fig. 4c). The effect of NT on crop yield in different climates was not consistent. In arid climates, NT soil management caused 10.2% greater crop yield, but in humid climates, NT decreased yield by 7.5%, compared to CT (Fig. 4d).

3.2.2. Soil texture and pH

Generally, soil texture had no statistically significant effect on the difference between NT and CT in terms of soil GHG emissions or crop yield (Table 2). In fine textured soils, NT resulted in significantly higher (32.2%) N_2O emission (Fig. 4c). With NT, CO_2 emission was significantly lower, by 15.3% and 18.4%, in acidic and neutral soils, respectively (Fig. 4a). No-tillage also significantly reduced CH_4 emission by 25.2% in acidic soils (Fig. 4b). We found a significant decrease (31.2%) in CH_4 uptake in neutral soils with NT (Fig. S1a). Differences in N_2O emissions between NT and CT were not significantly influenced by soil pH although there was a nearly 15% greater emission from acidic soils in NT (Fig. 4c, Table 2). For crop yield, our results suggested that NT improved yield (13.1%) in alkaline soils (Fig. 4d).

3.3. Interactive controls of management practices with CT and NT

3.3.1. Nitrogen fertilization

Nitrogen fertilizer application rate did not significantly affect the difference in soil GHG emissions between NT and CT (Table 2). Compared to CT, NT significantly reduced CH_4 emission (24.7%) at the medium N fertilizer rate (Fig. 5b), and it resulted in significantly higher N_2O emission (16.7%) at the high fertilizer rate (Fig. 5c). However, N fertilizer rate played a significant role in crop yield differences between

Table 2
Summary of the Chi square test for the variables controlling the comparative effect of tillage (no tillage vs. conventional tillage) on GHG emissions and crop yield.

Variables	CO_2		CH_4			N_2O		GHG		Yield	
	df	χ^2	df	χ_1^2	χ_2^2	df	χ^2	df	χ^2	df	χ^2
Crop types	3	18.24^{***}	2	9.56^{**}	7.76*	3	1.14	3	13.77**	3	42.96^{***}
Climate	1	5.42^{**}	1	1.12	4.9*	1	0.22	1	0.2	1	10.95^{***}
Duration	1	13.96^{***}	1	18.11^{***}	5.25	2	0.23	1	2.69	2	2.69
Texture	2	1.07	2	0.74	1.71	2	5.92	2	2.57	2	1.85
pH	2	11.71^{**}	2	9.57^{**}	18.4^{***}	2	2.42	2	7.6*	2	5.91
N rate	3	0.53	3	3.88	6.9	3	2.56	3	2.21	3	10.08^{*}
N placement	1	0.6	1	0.13	0.56	1	10.44^{**}	1	0.21	1	5.09^{*}
Residue	1	4.04^{*}	1	0.63	2.46	1	0.15	1	0.8	1	0.16

^{df} represents degrees of freedom. χ_1^2 represents CH_4 emissions, χ_2^2 represents CH_4 uptakes.
Statistical significance: $*P < 0.05$; $**P < 0.01$; $***P < 0.001$.

NT and CT (Table 2). Specifically, NT enhanced crop yield (25.2%) at the low fertilizer N rate (Fig. 5d). Additionally, though the NT versus CT response patterns in N_2O emission and crop yield due to N fertilizer placement were similar (Fig. 5c, d), there was a significant difference between the two fertilization sub-groups (Table 2). Compared to CT, surface N fertilizer placement in NT exhibited 18.6% higher N_2O emission (Fig. 5c). Changes in N_2O emission due to the tillage practices were not significant with subsurface N placement. Fertilizer N placement had no effect on the differences in CO_2 emission or CH_4 flux between the tillage practices (Table 2).

3.3.2. *Residue management and duration of no-tillage*

Crop residue management only significantly affected CO_2 emission (Table 2). With crop residue removal, CO_2 emission was significantly lower (-15.8%) in NT (Fig.5a). However, with residue retention, there was no significant difference in CO_2 emission between the tillage practices. Changes in CH_4 and N_2O fluxes and crop yield due to NT were not influenced by residue management. The duration of NT had inconsistent effects on CO_2 and CH_4 emissions. Emissions of CO_2 and CH_4 were reduced by 13.3% and 21.4%, respectively, with short NT duration (Fig. 5a, b), but there was no difference between NT and CT for studies where NT duration was longer than 5 years. The duration of NT had no impact on the differences in CH_4 uptake, N_2O emission, or crop

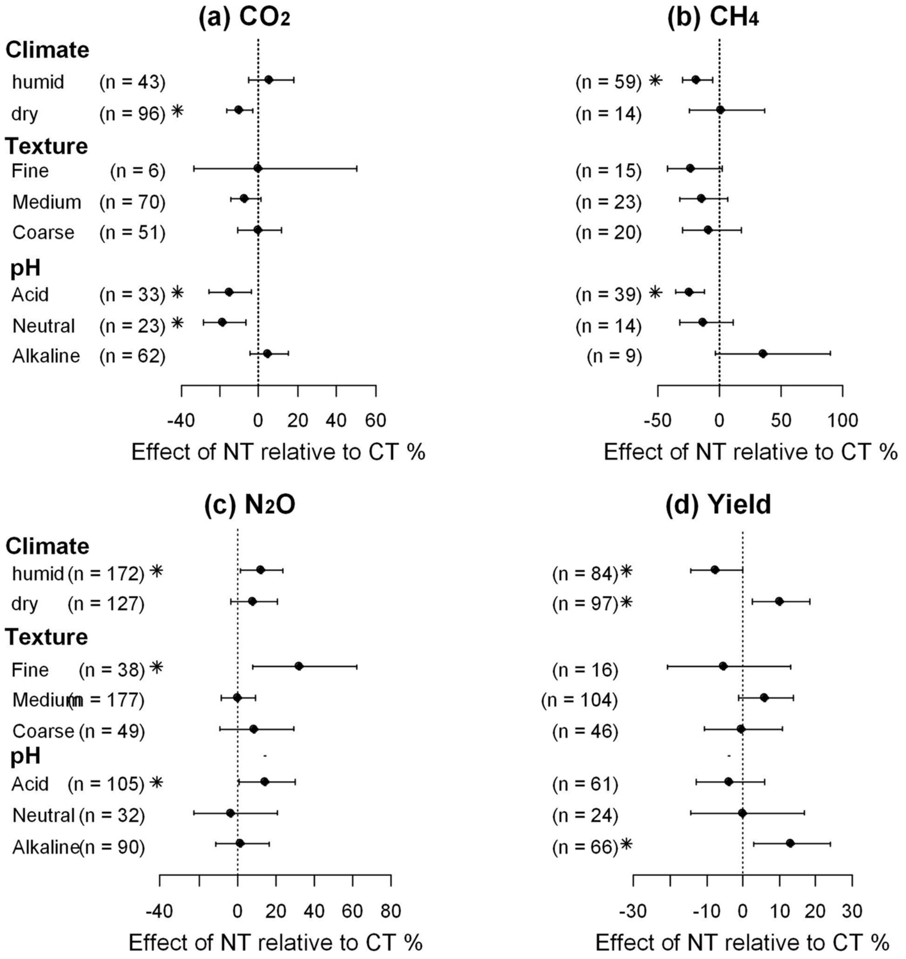

Fig. 4. The effect of NT on soil greenhouse gas (GHG) emissions and crop yields differed with environmental factors (a) CO_2 (b) CH_4 (c) N_2O (d) Yield. Numerals indicate the number of observations. * represents $p < 0.05$.

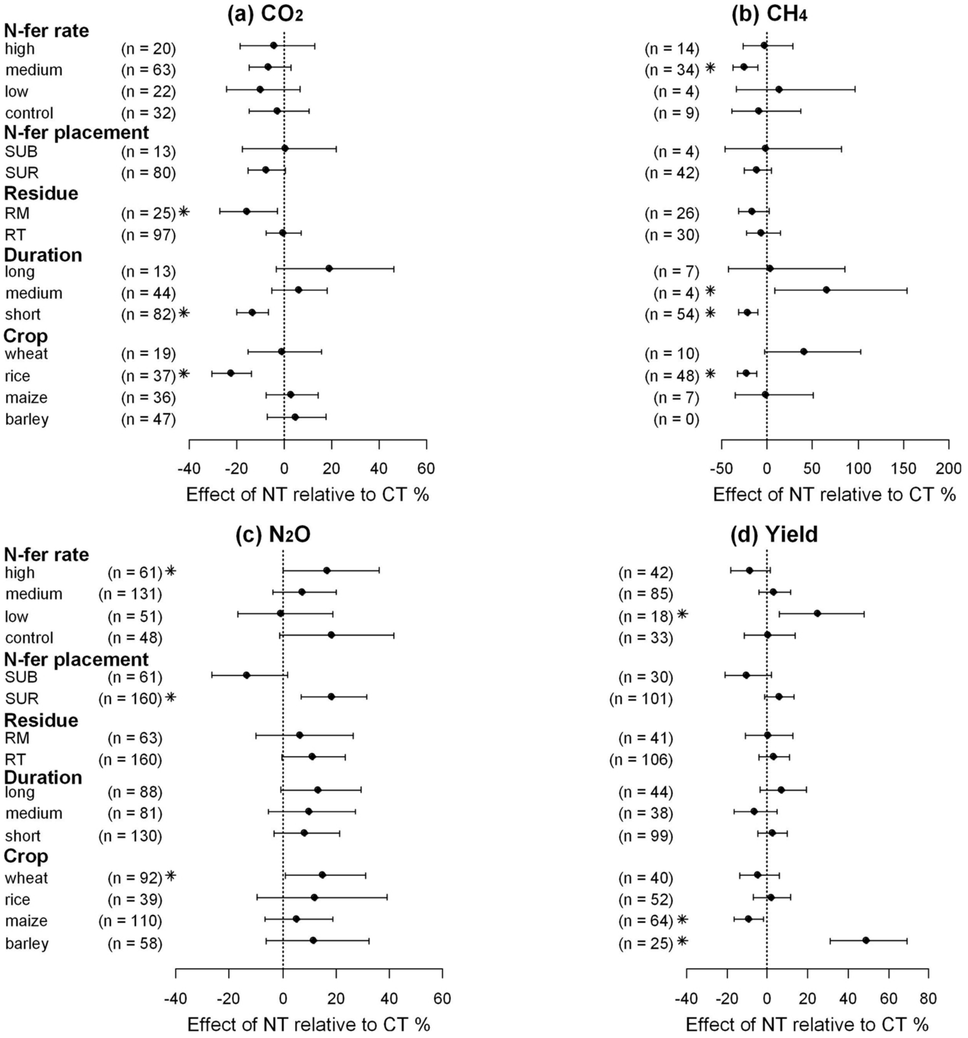

Fig. 5. The effect of NT on soil greenhouse gas (GHG) emissions and crop yields differed with management factors. (a) CO_2 (b) CH_4 (c) N_2O (d) Yield. Numerals indicate the number of observations. * represents $p < 0.05$.

yield.

3.3.3. Crop species

The crop species being grown played a significant role in the differences in GHG emissions and crop yield due to tillage (Table 2). The difference in CO_2 emission between NT and CT was largest with rice, where NT soils emitted 22.5% less CO_2 than CT soils (Fig. 5a). No-tillage also reduced CH_4 emission in rice production systems by 22.4% (Fig. 5b), but it increased CH_4 uptake in wheat by 31.1% (Fig. S1b). There were no significant differences in CO_2 emission and CH_4 flux between the tillage practices in barley or maize production systems. Changes in N_2O emission between NT and CT were only significantly different with wheat production, where a 15.2% increase in emission under NT was noted (Fig. 5c). Crop yield differences between NT and CT were significant in barley and maize production systems, with barley yield being 49% higher and maize yield 9.3% lower in NT (Fig. 5d).

3.4. Effect of no-tillage on global warming potential

For those studies that measured fluxes of all three GHGs, NT exhibited no difference in GWP compared to CT (Fig. 6). Further examination of relevant environment and management variables showed that soil pH and crop species significantly affected the difference in GWP between tillage systems (Table 2). No-tillage decreased GWP by 31.2% in acidic soils and by 24.8% in rice fields (Fig. 6). This pattern generally matched the effect of NT on CO_2 flux (Figs. 4 and 5). However, with the realization that fluxes of all three GHGs and crop yield

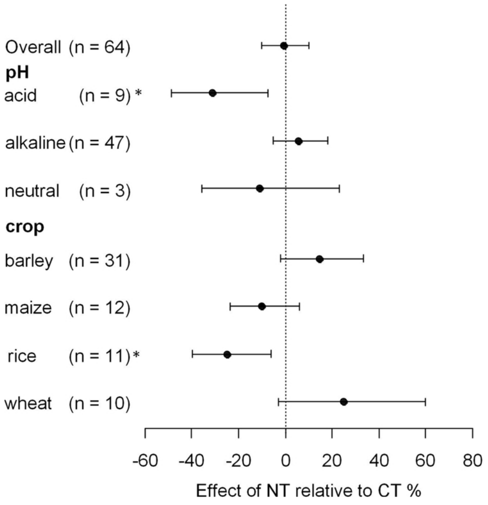

Fig. 6. The effect of NT on the global warming potential (GWP) of greenhouse gas (GHG) emissions. Numerals indicate the number of observations. * represents $p < 0.05$.

were reported in few studies comparing NT and CT, these results were likely affected by publication bias (Table S1), and therefore should be interpreted cautiously.

4. Discussion

4.1. Responses of GHG emissions to NT

Our meta-analysis found no significant effect of NT on CO_2 emission. This contrasts with the results of an earlier meta-analysis documenting a significant decrease in CO_2 emission (-21%) with NT (Abdalla et al., 2016). This discrepancy might be related to data source differences. In Abdalla et al. (2016), data were collected from experiments in which CO_2 emission was only measured for a period immediately after tillage - not for the entire growing season. This shortened measurement period may have amplified the impact of tillage on CO_2 emission, as it possibly captures the release of CO_2 previously trapped in soil pores (Oorts et al., 2007). The immediate stimulation of tillage on CO_2 production was likely due to the breakdown of aggregates and exposure of otherwise protected SOM (Fiedler et al., 2016). Thus, short-duration studies might not be sufficient to capture the magnitude of CO_2 emission associated with season-long decay of surface crop residues in NT (Oorts et al., 2007). The response of GHG fluxes to NT varies considerably with GHG flux measurement timing (Regina and Alakukku, 2010). Although NT management has often been touted to reduce CO_2 emission (Kessavalou et al., 1998), greater CO_2 emission in NT has also been reported. This is likely due to the decomposition of crop residues accumulated in long-term NT (Oorts et al., 2007) or to enhanced soil respiration by a more abundant soil microbial population (Plaza-Bonilla et al., 2014b).

No-tillage decreased soil CH_4 emission by 15.5% and had no effect on soil CH_4 uptake, which is consistent with another meta-analysis reported for Chinese rice paddies (Zhao et al., 2016). Generally, rice paddies act as atmospheric CH_4 sources, while upland soils are either CH_4 sinks or sources, depending on the balance between soil methanogenic and methanotrophic activities (Topp and Pattey, 1997). Soil properties such as SOC, temperature, and bulk density play a leading role in controlling the activity of methanogens and methanotrophs, affecting the direction of CH_4 flux (Mitra et al., 2002). On one hand, NT results in higher surface SOC, soil water content and bulk density (Ahmad et al., 2009; Zhang et al., 2015), thus increasing the potential for CH_4 production due to greater availability of organic substrates and formation of anaerobic microsites. On the other hand, NT increases soil macroporosity and soil pore continuity (Ball et al., 1999), thus improving gas diffusivity and increasing CH_4 oxidation.

Our meta-analysis found that NT significantly increased soil N_2O emission by 10.4%. Higher N_2O emission in NT is usually ascribed to enhanced soil microbial activities, especially denitrification, due to increased soil moisture and decreased soil aeration (Venterea et al., 2005; Almaraz et al., 2009; Ma et al., 2013). Our results were different from some other studies. For example, Gregorich et al. (2008) observed higher N_2O emission from CT soils, and these authors suggested that nitrification (NO_3^- formation) was controlling N_2O emission from soils in CT due to greater soil aeration and lower soil water content. The contradictory findings might result from different microbial activity in responses to site-specific conditions. Microbial community may vary from site to site and interact with NT management, leading to different responses of N_2O emission.

4.2. Factors in regulating GHG emissions

4.2.1. Environmental factors

Climate greatly influenced the differences in GHG emissions between tillage practices (Table 2). For instance, NT strongly reduced CO_2 emission in dry climates. Similar trends in CO_2 emission in NT have been reported (Abdalla et al., 2016). The larger difference between NT and CT in dry climates can be attributed to the differences in soil temperature (Lu et al., 2016) and soil water availability (Álvaro-Fuentes et al., 2008). No-tillage normally causes greater soil water content than does CT (Abdalla et al., 2013). The resulting difference in soil moisture between tillage practices tends to be large at dry sites (Feiziene et al., 2012) and so does the difference in soil temperature (Lu et al., 2016). In terms of the tillage effects on CH_4 emission, although there was a great reduction with NT in humid climates, climate regime had no significant influence (Table 2). A 90% decrease in the NT soil CH_4 emission was observed by Sapkota et al. (2015) in a semi-arid rice field, which was largely attributed to a different water management strategy that caused a shorter flooding period in the NT plots. Continuous flooding can be a major factor controlling CH_4 production because as soil redox potential falls below -150 mV, methanogenesis is favored (Masscheleyn et al., 1993). Considering that NT soils maintain an improved moisture regime, irrigation schedules with shortened flooding periods can be expected to reduce rice field CH_4 emission, regardless of the climate regime. In regard to N_2O, there was significantly higher emission with NT, relative to CT, in humid climates. Humid climates, which exhibit higher precipitation frequency, combined with greater NT soil moisture promote denitrification driven N_2O emission. Total N_2O emission depends on how long favorable conditions persist (Hunt et al., 2016). This is supported by Almaraz et al. (2009), who found that precipitation is the major driver of N_2O emission and that differences between NT and CT in N_2O emission are significantly larger in a wet year than a dry year.

The significant increase in N_2O emission in fine-textured NT soils (Fig. 4c) is noteworthy, and it is consistent with previous studies (Rochette, 2008). Soil texture may modify the effects of NT on N_2O emission via differences in soil water content (Abdalla et al., 2013). Rochette (2008) reported increased N_2O emission from poorly-drained fine-textured soils in NT located in regions with humid climates. Implementing NT in fine-textured soils in humid areas increased N_2O emission by approximately 38% compared to CT (Table S2). This indicates that climate-soil interactions should be considered before adopting NT as a CSA practice in a certain region.

The impact of NT on GHG emissions was sensitive to soil acidity. In acidic soils, CO_2 and CH_4 emissions were reduced but N_2O emission increased with NT management. Soil pH can affect GHG production in soils and pH can also be affected by different tillage regimes. Microbial activity, the major source of soil CO_2 emission and often globally expressed as respiration, is sensitive to soil pH. Increased basal respiration with increased pH has been widely reported (Lundström et al., 2003). As NT management is known to result in reduced topsoil pH (Dick, 1983), decreased dissolved organic carbon and CO_2 emission is expected. The optimum soil pH for CH_4 production is near neutrality. Considering methanogenic bacteria are acid sensitive, a small decrease in soil pH can substantially reduce CH_4 production, whereas a slight increase in soil pH can produce the opposite response (Wang et al., 1993). Higher N_2O emission from acidic soils can be ascribed to the greater sensitivity of N_2O reductase to low pH than that of the other denitrification reductases (Thomsen et al., 1994). This can result in a higher ratio of N_2O to N_2 as pH declines, and therefore greater N_2O loss from low pH soils (Baggs et al., 2010).

4.2.2. Management factors

Differences in CO_2 emission between NT and CT did not differ with N fertilizer rate or placement, which agreed with Plaza-Bonilla et al. (2014b) and Snyder et al. (2009). Similar results were reported by Abdalla et al. (2016) and may be attributed to the overriding impact of N fertilization in enhancing productivity and carbon inputs to both NT and CT soils. Similarly, N fertilization did not significantly alter the differences in CH_4 emission between the tillage practices. However, N fertilization is considered the main stimulus to increased agroecosystem N_2O emission (Grace et al., 2011). A sharp rise in N_2O emission within days of fertilization is commonly observed in both NT and CT

(Halvorson et al., 2008; Sapkota et al., 2015). Compared with CT, soil environmental and physical conditions in NT are expected to be conducive to greater denitrifying activity and greater likelihood of N_2O emission following surface application of N fertilizer (Venterea et al., 2005). Soil organic matter and microbial population are usually more uniformly distributed with depth in CT. The vertical distribution of potential denitrifying activity varies with tillage, with higher facultative anaerobe populations and potential denitrification rates in the topsoil of NT compared to CT (Linn and Doran, 1984aa; Groffman, 1985).

Surface placement of N fertilizer likely provides adequate substrate to the more abundant population of denitrifiers in the NT soil surface. This, together with a wetter and denser soil environment, enhances denitrifying N_2O emission. With subsurface N fertilizer application, less N_2O emission under NT could result from lower denitrifier populations and/or available C concentration at the greater depth (Drury et al., 2006), relative to CT soils. The greater water-filled pore space observed in NT may also increase the probability of reduction of N_2O to N_2 during upward diffusion (Linn and Doran, 1984b), further reducing N_2O emission with subsurface N fertilizer placement.

Tillage is often associated with residue management. There were indirect effects of residue management on differences in GHG emissions between the tillage practices. With residue removal, the reduction in CO_2 emission was greater in NT than CT. This was expected considering that NT has little effect on SOM turnover rate, while CT accelerates SOM turnover via thorough surface soil disturbance. However, large uncertainties in the responses of GHG emissions exist when considering the opposite operation, residue retention, as both residue quantity and quality are important to soil physical and chemical properties (Abdalla et al., 2016). For example, the quantity of maize residue is usually twice that of soybean, but soybean residue decomposes rapidly due to a lower C:N ratio. These, together, can lead to higher SOM with maize residues. Residue retained in NT remains at the soil surface with minimal disturbance while CT causes some residue incorporation. Consequently, the content of SOM is higher in the uppermost surface 20 cm of NT soils but it is relatively homogeneously distributed with depth in the surface 20 cm of CT soils (Ziadi et al., 2014). Therefore, the decomposition rate of SOM was largely affected by its distribution in the upper soil layer. As the duration of NT management increases, the contribution of older weathered residue to CO_2 emission rises (Oorts et al., 2007). In our analysis, long-term NT with residue retention gave a nearly 26% greater CO_2 emission (Table S3).

Differences in CO_2 and CH_4 emissions between the tillage practices became non-significant with time (Fig. 5a, b). With short-term NT duration, CO_2 and CH_4 emissions were significantly reduced relative to those with CT, but the differences decreased with longer NT duration. Significantly larger soil carbon stocks in long-term NT made carbon emissions equal to those from the smaller CT soil carbon stocks (Oorts et al., 2007). A new equilibrium, in both tillage systems, between carbon inputs and outputs may have formed. However, in experiments where NT was short-term, the CT and NT soils may not have yet reached the anticipated equilibrium.

Differences in GHG emissions between the tillage practices varied with crop species. Rice production is more likely, among the four crop species evaluated, to exhibit reduced CO_2 and CH_4 emissions with NT adoption. The surface NT soil bulk density was significantly greater than that of CT soil (Ahmad et al., 2009; Li et al., 2013). Li et al. (2013) speculated that CH_4 produced in NT soil might be better retained due to soil surface compaction, thereby making CH_4 oxidation by methanotrophic bacteria more likely. Increased bulk density reduces macroporosity, which inhibits organic matter decomposition (Ahmad et al., 2009). This reduces dissolved organic carbon concentration that restricts substrate supply to methanogens and further reduces CH_4 production. These NT effects are exclusively significant in paddy rice production because the waterlogged environment otherwise favors CH_4 production. Wheat production can enhance SOC and total N sequestration, particularly in NT (Wright et al., 2007), which provides sufficient substrate for N_2O production and possibly explains the larger increase in N_2O emission with NT wheat production.

4.3. Crop yield and the GWP of GHG emissions

In general, our meta-analysis found no significant effect of NT, relative to CT, on crop yield. Previous studies reported slight yield reduction (about 5%) with NT (van Kessel et al., 2013; Pittelkow et al., 2015). The difference might be because we only analyzed yield data from research trials that included GHG measurements. Great variation was found in the yield dataset. Much of the increased yield in NT was contributed by studies in barley production (Fig. 5d). Plaza-Bonilla et al. (2014a) reported six-fold greater NT barley yield in a rain fed Mediterranean climate due to better water use efficiency. Pittelkow et al. (2015) further suggested that NT performs better than CT in rain fed conditions in dry climates. Our results concur with these observations. Most (24 out of 25) of the barley yield trials in this meta-analysis were in the dry climate subgroup. Considering there was less of an N_2O emission increase, and a greater decrease in CO_2 emission in NT in dry climates (Fig. 4a, c), NT would be the better management practice for climate change mitigation goals. Our observations that NT increased crop yield by 13.1% in alkaline soils (Fig. 4d) and by 25.2% at the low N fertilizer rate (Fig. 5d) were also noteworthy. Additionally, NT exhibited similar GHG emissions to CT in alkaline soils or with low N fertilizer input. These observations suggest that NT can be the better choice under such circumstances.

In terms of climate change mitigation, there is a general consensus that NT can enhance soil carbon sequestration. However, whether this benefit would be offset by NT's stimulation of N_2O emission is still under debate. In this meta-analysis, overall GWP was not different between NT and CT. This suggested that a balance between N_2O emission and carbon sequestration under NT can be reached (Halvorson et al., 2008). Moreover, NT induced GWP reductions may not be coincident with yield loss, particularly on acidic soils and with rice production. Considering the other benefits that accompany NT adoption such as lower labor and machinery inputs, NT may be an effective practice that further mitigates climate change through reduced fossil fuel consumption.

Accordingly, NT implementation can contribute to food security and climate change mitigation. However, interactions between NT and site-specific conditions, including other management practices, could offset NT's benefits. Future NT research should include more field measurements chosen to consider other complicating environment or management factors. For example, measurements of GHG emissions should be for the whole year as this may better reflect the full expression of emission differences between NT and CT. Due to the limitations in available data, this study focused only on the GHG emissions during the growing season. Emissions during non-growing season, especially in regions that experience freeze-thaw cycles and snow cover, could be significant and should not be ignored at study sites in these regions. Moreover, analysis of the NT effect from different space and time scales is needed to better identify NT's effectiveness in the context of global change. While meta-analysis is better positioned than individual studies as an effective methodology to generate more informed and accurate conclusions, it depends on data quality and quantity, especially for large scale assessment. The lack of certain meta-data (e.g., fertilization methods, residue management, and soil properties) in some studies made it difficult to include their results in this meta-analysis. Thus, publications should clearly describe weather conditions, site management/field operations, and soil properties. In addition, more tillage research regarding all three GHG emissions, measured using similar methods, is needed to draw more representative conclusions regarding tillage choices and resulting GWP.

5. Conclusions

This study provided a comprehensive and quantitative synthesis of NT and CT effects on GHG emissions and crop yield in different cropping systems. In general, NT can reduce CH_4 emission by 15.5% with a concomitant increase in N_2O emission of 10.4%. These effects seem to diminish with long-term duration of NT. Thus, the combination of NT with other climate-smart agriculture (CSA) components might be needed. Although NT cannot reduce all three GHG emissions simultaneously, there is some evidence of a reduction in overall GWP in NT given specific conditions, which needs to be verified with further observations. Emission of CO_2 can be significantly reduced, with a yield benefit, with NT adoption in dry climates. However, in humid climates, NT tended to increase N_2O emission and reduce crop yield, suggesting cautious consideration of NT adoption in humid regions. Soil pH was also important, and implementing NT can help mitigate climate change on acidic soils and enhance food security on alkaline soils because total GWP was reduced in NT without yield penalty on acidic soils, and NT increased crop yield without affecting GWP on alkaline soils. No-tillage and a low N fertilizer rate increased crop yield without exacerbating GHG emissions compared to CT. Furthermore, subsurface N fertilizer placement in NT should be considered to reduce N_2O emission. Among the four cereal crops, there was a large reduction in GWP with NT rice production, with no yield penalty. A yield benefit was only observed for barley, while there was a maize yield loss. These results credit NT for enhancing climate change mitigation and food security in rice and barley production, respectively. Overall, this study provides both support and caution to the adoption of NT as a CSA management practice. To identify other CSA management practices that are suitable at local, regional and/or global scales, future CSA research programs that systematically investigate agroecosystem responses (e.g., crop yield, GHG emissions) using diverse methods (e.g., observation, meta-analysis, and agroecosystem modeling) are needed.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2018.09.002.

References

Linn, D., Doran, J., 1984a. Aerobic and anaerobic microbial populations in no-till and plowed soils. Soil Sci. Soc. Am. J. 48, 794–799.

Abdalla, M., Osborne, B., Lanigan, G., Forristal, D., Williams, M., Smith, P., Jones, M., 2013. Conservation tillage systems: a review of its consequences for greenhouse gas emissions. Soil Use Manage. 29, 199–209.

Abdalla, K., Chivenge, P., Ciais, P., Chaplot, V., 2016. No-tillage lessens soil CO_2 emissions the most under arid and sandy soil conditions: results from a meta-analysis. Biogeoscience 13, 3619–3633.

Ahmad, S., Li, C., Dai, G., Zhan, M., Wang, J., Pan, S., Cao, C., 2009. Greenhouse gas emission from direct seeding paddy field under different rice tillage systems in central China. Soil Tillage Res. 106, 54–61.

Almaraz, J., Mabood, F., Zhou, X., Madramootoo, C., Rochette, P., Ma, B., Smith, D., 2009. Carbon dioxide and nitrous oxide fluxes in corn grown under two tillage systems in southwestern Quebec. Soil Sci. Soc. Am. J. 73, 113–119.

Álvaro-Fuentes, J., López, M., Arrúe, J., Cantero-Martínez, C., 2008. Management effects on soil carbon dioxide fluxes under semiarid Mediterranean conditions. Soil Sci. Soc. Am. J. 72, 194–200.

Baggs, E., Smales, C., Bateman, E., 2010. Changing pH shifts the microbial sourceas well as the magnitude of N_2O emission from soil. Biol. Fert. Soils (46), 793–805.

Ball, B.C., Dobbie, K.E., Parker, J.P., Smith, K.A., 1997. The influence of gas transport and porosity on methane oxidation in soils. J. Geophys. Res. Atmos. 102, 23301–23308.

Ball, B., Scott, A., Parker, J., 1999. Field N_2O, CO_2 and CH_4 fluxes in relation to tillage, compaction and soil quality in Scotland. Soil Tillage Res. 53, 29–39.

Begg, C.B., Mazumdar, M., 1994. Operating characteristics of a rank correlation test for publication bias. Biometrics 50, 1088–1101.

Chatskikh, D., Olesen, J., 2007. Soil tillage enhanced CO_2 and N_2O emissions from loamy sand soil under spring barley. Soil Tillage Res. 97, 5–18.

Daryanto, S., Wang, L., Jacinthe, P., 2017a. Impacts of no-tillage management on nitrate loss from corn, soybean and wheat cultivation: a meta-analysis. Sci. Rep. 7, 12117.

Daryanto, S., Wang, L., Jacinthe, P., 2017b. Global synthesis of drought effects on cereal, legume, tuber and root crops production: a review. Agric. Water Manag. 179, 18–33.

Deng, Q., Hui, D., Dennis, S., Reddy, K., 2017. Responses of terrestrial ecosystem phosphorus cycling to nitrogen addition: a meta-analysis. Global Ecol. Biogeogr. 26, 713–728.

Derpsch, R., Friedrich, T., Kassam, A., Li, H., 2010. Current status of adoption of no-till farming in the world and some of its main benefits. Int. J. Agric. Biol. Eng. 3, 1–25.

Dick, W., 1983. Organic carbon, nitrogen, and phosphorus concentrations and pH in soil profiles as affected by tillage intensity. Soil Sci. Soc. Am. J. 47, 102–107.

Dinnes, D.L., 2004. Assessment of Practices to Reduce Nitrogen and Potassium Non-point Source Pollution of Iowa's Surface Waters. Iowa Department of National Resources, Des Moines, LA.

Drury, C., Reynolds, W., Tan, C., Welacky, T., Calder, W., McLaughlin, N., 2006. Emissions of nitrous oxide and carbon dioxide. Soil Sci. Soc. Am. J. 70, 570–581.

Drury, C., Reynolds, W., Yang, X., McLaughlin, N., Welacky, T., Calder, W., Grant, C., 2012. Nitrogen source, application time, and tillage effects on soil nitrous oxide emissions and corn grain yields. Soil Sci. Soc. Am. J. 76, 1268–1279.

Fangueiro, D., Becerra, D., Albarrán, Á., Peña, D., Sanchez-Llerena, J., Rato-Nunes, J., LópezPiñeiro, A., 2017. Effect of tillage and water management on GHG emissions from Mediterranean rice growing ecosystems. Atmos. Environ. 150, 303–312.

FAO, 2011. Save and Grow: a Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

FAO, 2013. Climate-smart Agriculture: Sourcebook. Food and Agriculture Organization of the United Nations (FAO), Rome, Italy.

FAO, 2014. Food and Agriculture Organization of the United Nations Statistics Division (FAOSTAT). http://www.fao.org/faostat/en/#data/QC (Accessed 11 September 2017). .

Farooq, M., Flower, K., Jabran, K., Wahid, A., Siddique, K., 2011. Crop yield and weed management in rainfed conservation agriculture. Soil Tillage Res. 117, 172–183.

Feiziene, D., Feiza, V., Kadziene, G., Vaideliene, A., Povilaitis, V., Deveikyte, I., 2012. CO2 fluxes and drivers as affected by soil type, tillage and fertilization. Acta Agric. Scand. B 62, 311–328.

Fiedler, S., Leinweber, P., Jurasinski, G., Eckhardt, K., Glatzel, S., 2016. Tillage-induced short-term soil organic matter turnover and respiration. Soil 2, 475–486.

Grace, P., Philip Robertson, G., Millar, N., Colunga-Garcia, M., Basso, B., Gage, S., Hoben, J., 2011. The contribution of maize cropping in the Midwest USA to global warming: a regional estimate. Agric. Syst. 104, 292–296.

Grandy, A., Loecke, T., Parr, S., Robertson, G., 2006. Long-term trends in nitrous oxide emissions, soil nitrogen, and crop yields of till and no-till cropping systems. J. Environ. Qual. 35, 1487–1495.

Gregorich, E., Rochette, P., St-Georges, P., McKim, U., Chan, C., 2008. Tillage effects on N_2O emission from soils under corn and soybeans in Eastern Canada. Can. J. Soil Sci. 88, 153161.

Groffman, P.M., 1985. Nitrofication and denitrification in conventional and no-tillage soils. Soil Sci. Soc. Am. J. 49, 329–334.

Halvorson, A., Del Grosso, S., Reule, C., 2008. Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems. J. Environ. Qual. 37, 1337–1344.

Havlin, J.L., Beaton, J.D., Tisdale, S.L., Nelson, W.L., 2013. Soil Fertility and Fertilizers: An Introduction to Nutrient Management, 8th ed. Pearson Inc., Upper Saddle River, New Jersey pp. 50.

He, J., Li, H., Rasaily, R., et al., 2011. Soil properties and crop yields after 11 years of no tillage farming in wheat–maize cropping system in North China Plain. Soil Tillage Res. 113, 48–54.

Hedges, L., Gurevitch, J., Curtis, P., 1999. The meta-analysis of response ratios in experimental ecology. Ecology 80, 1150–1156.

Hijmans, R., Cameron, S., Parra, J., Jones, P., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978.

Hunt, D., Bittman, S., Zhang, H., Bhandral, R., Grant, C., Lemke, R., 2016. Effect of polymercoated urea on nitrous oxide emission in zero-till and conventionally tilled silage corn. Can. J. Soil Sci. 96, 12–22.

IPCC, 2013. Climate change 2013: the physical science basis. In: Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, K.S., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA.

IPCC, 2014. climate change 2014: mitigation of climate change. In: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., Minx, J.C. (Eds.), Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kessavalou, A., Mosier, A., Doran, J., Drijber, R., Lyon, D., Heinemeyer, O., 1998. Fluxes of carbon dioxide, nitrous oxide, and methane in grass sod and winter wheat-fallow tillage management. J. Environ. Qual. 27, 1094–1104.

Kim, S.Y., Gutierrez, J., Kim, P.J., 2016. Unexpected stimulation of CH_4 emissions under continuous no-tillage system in mono-rice paddy soils during cultivation. Geoderma 267, 40.

Lal, R., 2015. Sequestering carbon and increasing productivity by conservation agriculture. J. Soil Water Conserv. 70, 55A–62A.

Lal, R., Follett, R., Stewart, B., Kimble, J., 2007. Soil carbon sequestration to mitigate climate change and advance food security. Soil Sci. 172, 943–956.

Li, D., Liu, M., Cheng, Y., Wang, D., et al., 2011. Methane emissions from double-rice cropping system under conventional and no tillage in southeast China. Soil Till. Res. 113, 77–81.

Li, C., Zhang, Z., Guo, L., Cai, M., Cao, C., 2013. Emissions of CH_4 and CO_2 from double rice cropping systems under varying tillage and seeding methods. Atmos. Environ. 80, 438–444.

Linn, D., Doran, J., 1984b. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and nontilled soils. Soil Sci. Soc. Am. J. 48, 1267–1272.

Lipper, L., Thornton, P., Campbell, B., et al., 2014. Climate-smart agriculture for food security. Nat. Clim. Change 4, 1068–1072.

Lipsey, M.W., Wilson, D.B., 2001. Practical Meta-Analysis. Sage Publications, Thousand Oaks, USA.

Lu, X., Lu, X., Tanveer, S., Wen, X., Liao, Y., 2016. Effects of tillage management on soil CO_2 emission and wheat yield under rain-fed conditions. Arid. Soil Res. Rehabil. 54, 38–48.

Lundström, U.S., Bain, D.C., Taylor, A.F.S., van Hees, P.A.W., 2003. Effects of acidification and its mitigation with lime and wood ash on forest soil processes: a review. Water Air Soil Pollut.: Focus 3, 5–28.

Ma, Y., Sun, L., Zhang, X., et al., 2013. Mitigation of nitrous oxide emissions from paddy soil under conventional and no-till practices using nitrification inhibitors during the winter wheat-growing season. Biol. Fertil. Soils 49, 627–635.

Masscheleyn, P., DeLaune, R., Patrick, W., 1993. Methane and nitrous oxide emissions from laboratory measurements of rice soil suspension: effect of soil oxidation-reduction status. Chemosphere 26, 251–260.

Mitra, S., Wassmann, R., Jain, M.C., Pathak, H., 2002. Properties of rice soils affecting methane production potentials: 1. Temporal patterns and diagnostic procedures. Nutr. Cycl. Agroecosyst. 64, 169–182.

Ogle, S., Swan, A., Paustian, K., 2012. No-till management impacts on crop productivity, carbon input and soil carbon sequestration. Agric. Ecosyst. Environ. 149, 37–49.

Oorts, K., Merckx, R., Gréhan, E., Labreuche, J., Nicolardot, B., 2007. Determinants of annual fluxes of CO_2 and N_2O in long-term no-tillage and conventional tillage systems in northern France. Soil Tillage Res. 95, 133–148.

Pittelkow, C., Linquist, B., Lundy, M., et al., 2015. When does no-till yield more? A global meta-analysis. Field Crops Res. 183, 156–168.

Plaza-Bonilla, D., Álvaro-Fuentes, J., Arrúe, J., Cantero-Martínez, C., 2014a. Tillage and nitrogen fertilization effects on nitrous oxide yield-scaled emissions in a rainfed Mediterranean area. Agric. Ecosyst. Environ. 189, 43–52.

Plaza-Bonilla, D., Cantero-Martínez, C., Bareche, J., Arrúe, J., Álvaro-Fuentes, J., 2014b. Soil carbon dioxide and methane fluxes as affected by tillage and N fertilization in dryland conditions. Plant Soil 381, 111–130.

Prajapati, P., Jacinthe, P.A., 2014. Methane oxidation kinetics and diffusivity in soils under conventional tillage and long-term no-till. Geoderma 230, 161–170.

Regina, K., Alakukku, L., 2010. Greenhouse gas fluxes in varying soils types under conventional and no-tillage practices. Soil Tillage Res. 109, 144–152.

Rochette, P., 2008. No-till only increases N2O emissions in poorly-aerated soils. Soil Tillage Res. 101, 97–100.

Rohatgi, A., 2012. WebPlotDigitalizer: HTML5 Based Online Tool to Extract Numerical Data From Plot Images. Version 3. (Accessed December 2016). http://arohatgi.info/WebPlotDigitizer/index.html.

Rosenberg, M.S., 2005. The file-drawer problem revisited: a general weighted method for calculating fail-safe numbers in meta-analysis. Evolution 59, 464–468.

Ruan, L., Robertson, G., 2013. Initial nitrous oxide, carbon dioxide, and methane costs of converting conservation reserve program grassland to row crops under no-till vs. conventional tillage. Glob. Change Biol. Bioenergy 19, 2478–2489.

Rusinamhodzi, L., Corbeels, M., van Wijk, M., Rufino, M., Nyamangara, J., Giller, K., 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. Agron. Sustain. Dev. 31, 657–673.

Sapkota, T., Jat, M., Shankar, V., Singh, L., Rai, M., Grewal, M., Stirling, C., 2015. Tillage, residue and nitrogen management effects on methane and nitrous oxide emission from rice– wheat system of Indian Northwest Indo-Gangetic Plains. J. Integer. Environ. Sci. 12, 31–46.

Sheehy, J., Six, J., Alakukku, L., Regina, K., 2013. Fluxes of nitrous oxide in tilled and no-tilled boreal arable soils. Agric. Ecosyst. Environ. 164, 190–199.

Snyder, C., Bruulsema, T., Jensen, T., Fixen, P., 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agric. Ecosyst. Environ. 133, 247–266.

Thomsen, J.K., Geest, T., Cox, R.P., 1994. Mass spectrometric studies of the effect of pH on the accumulation of intermediates in denitrification by Paracoccus denitrificans. Appl. Environ. Microbiol. 60, 536–541.

Topp, E., Pattey, E., 1997. Soils as sources and sinks for atmospheric methane. Can. J. Soil Sci. 167–177.

UNEP, 1997. In: Middleton, N., Thomas, D. (Eds.), World Atlas of Desertification, 2nd edn. Edward Arnold, London.

van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M., Linquist, B., van Groenigen, K., 2013. Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: a meta-analysis. Glob. Change Biol. Bioenergy 19, 33–44.

Venterea, R., Burger, M., Spokas, K., 2005. Nitrogen oxide and methane emissions under varying tillage and fertilizer management. J. Environ. Qual. 34, 1467–1477.

Wang, Z., DeLaune, R., Patrick, W., Masscheleyn, P., 1993. Soil redox and pH effects on methane production in a flooded rice Soil. Soil Sci. Soc. Am. J. 57, 382–385.

WRI, 2014. Climate Analysis Indicators Tool (CAIT). Available online at:. World Resources Institute, Washington, DC (Accessed October 2017). http://cait.wri.org.

Wright, A., Dou, F., Hons, F., 2007. Crop species and tillage effects on carbon sequestration in subsurface soil. Soil Sci. 172, 124–131.

Yao, Z., Zheng, X., Wang, R., Xie, B., Butterbach-Bahl, K., Zhu, J., 2013. Nitrous oxide and methane fluxes from a rice–wheat crop rotation under wheat residue incorporation and notillage practices. Atmos. Environ. 79, 641–649.

Zhang, Y., Sheng, J., Wang, Z., Chen, L., Zheng, J., 2015. Nitrous oxide and methane emissions from a Chinese wheat–rice cropping system under different tillage practices during the wheat-growing season. Soil Tillage Res. 146, 261–269.

Zhang, Z., Cao, C., Guo, L., Li, C., 2016a. Emissions of CH_4 and CO_2 from paddy fields as affected by tillage practices and crop residues in central China. Paddy Water Environ. 14–92.

Zhang, Z., Chen, J., Liu, T., Cao, C., Li, C., 2016b. Effects of nitrogen fertilizer sources and tillage practices on greenhouse gas emissions in paddy fields of central China. Atmos. Environ. 144, 274–281.

Zhao, X., Liu, S., Pu, C., et al., 2016. Methane and nitrous oxide emissions under no-till farming in China: a meta-analysis. Glob. Change Biol. Bioenergy 22, 1372–1384.

Ziadi, N., Angers, D., Gagnon, B., Lalande, R., Morel, C., Rochette, P., Chantigny, M., 2014. Long-term tillage and synthetic fertilization affect soil functioning and crop yields in a corn–soybean rotation in eastern Canada. Can. J. Soil Sci. 94, 365–376.