Soil & Tillage Research 228 (2023) 105643

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

No tillage decreases GHG emissions with no crop yield tradeoff at the global scale

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ARTICLE INFO

Keywords:
Conservation tillage
Greenhouse gas fluxes
CO_2
N_2O
CH_4
Moderator variable
Meta-analysis

ABSTRACT

Conservation tillage has been widely adopted as an important and promising sustainable crop management option for mitigation of global climate warming. Although its effects on fluxes in greenhouse gases (GHGs) have been widely studied, contrasting results have been reported, where impacts of reduced and no tillage are unclear. Here, using a dataset with 1286 paired observations extracted from 147 publications, we systematically assessed the effects of reduced vs. no tillage on the fluxes of soil CO_2, N_2O, and CH_4 across the globe. We also assessed how reduced and no tillage may affect the total global warming potential (GWP) of these three GHGs and the associated crop yield. We found that (1) reduced tillage increases N_2O and CH_4 emissions by 31.0% and 24.7%, respectively, and decreases crop yields by 17.4%, with no effect on CO_2 emissions or CH_4 uptake; (2) no tillage decreases CO_2, N_2O, and CH_4 emissions, and GWP by an average of 15.1%, 7.5%, 19.8%, and 22.6%, respectively, with no effect on CH_4 uptake or crop yield; (3) crop residue retention, cropland type, rotation regime, crop species, and soil physicochemical properties regulate effects of reduced and no tillage, where their impact varies with GHG and tillage type; and (4) there was a lack of relationship between responses of crop yields and GHG fluxes under reduced and no tillage, with the exception of N_2O emissions, where they were positively related. Overall, our results showed that reduced tillage stimulates GHG emissions and decreases crop yields, whereas no tillage decreases GHG emissions, with no crop yield tradeoff. These results indicate that no tillage is an effective sustainable crop management practice for the mitigation of climate warming and provision of food security.

1. Introduction

Human activities have significantly contributed to global warming by increasing the concentration of important atmospheric greenhouse gases (GHGs) such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) (IPCC, 2014). Among all anthropogenic sources of GHGs, agriculture is estimated to be accountable for more than 12% of total emissions (IPCC, 2014). More attention has been recently paid to what changes could be made across agricultural management practices to mitigate GHG emissions. Conservation tillage, in contrast to conventional tillage, includes reduced and no tillage management approaches that aim to minimize the frequency or intensity of tillage operations in an effort to promote certain economic and environmental benefits (Unger and McCalla, 1980). Conservation tillage is also one of the three crop management principles invoked in conservation agriculture (FAO, 2011), and also remains a key component of climate-smart agriculture (Lipper et al., 2014). Conservation tillage has been widely adopted to minimize the degree and frequency of tillage passes and thus alleviate soil aggregate disruption and reduce soil erosion and organic matter losses (Singh et al., 2018). Conservation tillage may also contribute to increase soil organic carbon (SOC) accumulation, particularly in top-soils (West and Post, 2002; Zhao et al., 2015), and decrease the

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https://doi.org/10.1016/j.still.2023.105643
Received 17 May 2022; Received in revised form 22 November 2022; Accepted 4 January 2023
Available online 7 January 2023

emissions of soil-derived GHGs such as CO_2 and N_2O when compared with conventional tillage (Abdalla et al., 2016; Canadell and Schulze, 2014). Given that conservation tillage has been practiced on approximately 155 million ha in 2014 (FAO, 2014) and the area has been increasing, it is of great importance to quantitatively assess patterns and drivers of conservation tillage effects on the emission of multiple GHGs at the global scale.

Previous studies bring evidence of lower CO_2 emissions when moving from conventional to conservation tillage systems, especially when no tillage is adopted as main soil management practice (Abdalla et al., 2016; Reicosky, 1997; Ussiri and Lal, 2009). Several hypotheses have been proposed to explain the negative effects of conservation tillage on CO_2 emissions. For example, conservation tillage could protect soil carbon (C) stocks by reducing the disruption of soil aggregates and by limiting increases in soil temperature (He et al., 2011). In particular, by decreasing soil disturbance, conservation tillage limits microbial access to SOC pools thus reducing SOC decomposition and C loss from soil via CO_2 fluxes or from leaching (Six et al., 2004a, 2002). However, conservation tillage may also increase CO_2 emissions as a result of enhanced microbial activity caused by greater soil water availability (Plaza-Bonilla et al., 2014b).

Similarly, conservation tillage may also affect soil N_2O emissions through regulating soil moisture. Soil N_2O is generated by denitrification and nitrification of soil nitrogen (N), and the processes tend to be enhanced under higher moisture conditions with conservation tillage management (Smith and Conen, 2004). N_2O has a relatively high global warming potential (GWP) of 298 compared with those of CH_4 (21) and CO_2 (1) (IPCC, 2014). Previous studies show either positive (Lognoul et al., 2017), negative (Mutegi et al., 2010), or neutral (Guardia et al., 2016) effects of conservation tillage on N_2O emissions, suggesting that complex biogeochemical processes may regulate and explain such highly variable responses.

Fluxes of CH_4 may be affected by tillage practice, due to impacts on soil redox potential, aeration, structure, hydrology, and microbial activities, and crop growth (Mangalassery et al., 2014; Maucieri et al., 2021). For example, flooded rice paddies represent a key source of CH_4 emissions (Smith et al., 2008), whereas drained or well-aerated dryland soils act as a net sink of CH_4, due to greater levels of methanotrophy than methanogenesis (Saunois et al., 2016). Conservation tillage may reduce paddy CH_4 emissions, due to decreases in dissolved organic C, root growth, and aboveground biomass, and increases in soil porosity and moisture (Bayer et al., 2012; Zhang et al., 2013). However, there is also evidence for stimulated CH_4 missions from rice paddy soils under no tillage practice (Kim et al., 2016).

Conservation tillage effects on the fluxes of different soil GHGs can be influenced by a variety of moderator variables. For example, it has been shown that positive short-term effects of conservation tillage on N_2O emissions can shift to significant negative effects in the long-term (> 10 years) (Six et al., 2004b). Also, previous studies showed that residue retention can affect N_2O emissions through moderating the quality of soil C substrate as well as microbial N mineralization and nitrification (Chen et al., 2013; Mei et al., 2018). Additionally, soil physiochemical properties such as soil texture, pH, organic matter content, and nutrient concentration can play an important role in regulating conservation tillage effects. For example, soil texture can have either negative or positive effects on soil N_2O emission (Pelster et al., 2012; Weitz et al., 2001).

While a significant number of theoretical, experimental, and meta-analysis studies have investigated the effects of conservation tillage on the emission of different GHGs (Abdalla et al., 2016; Huang et al., 2018; Maucieri et al., 2021; Mei et al., 2018; Shakoor et al., 2021; Zhao et al., 2016), divergent and contradictory results were often found, and the focus of these studies tended to be on one or two types of GHGs, single conservation tillage approach (principally, no till) and cropland type, and limited in spatiotemporal scale, resulting in contrasting findings across agricultural systems and limited understanding of the effects and associated underlying mechanisms at the global scale. Thus, confirmation of the quantitative patterns and drivers of conservation tillage effects on global scale emissions of GHGs is required to improve agricultural mitigation of global climate warming.

Here, we conducted a global-scale meta-analysis, across staple crop types and climate regions, using paired observations extracted from peer reviewed studies reporting patterns and drivers of effects of reduced and no tillage on GHG fluxes and crop yield to evaluate impacts of conservation tillage approaches in sustainable staple crop production. The specific aims of this study were to evaluate global scale (1) effects of reduced and no tillage on emissions of CO_2 and N_2O, emissions and uptake of CH_4, total GWP of these three GHGs, and grain yield; (2) drivers of effects of reduced and no tillage effects on GHG fluxes, GWP, and yields of staple crops; and (3) relationships between conservation tillage mediated responses in staple crop GHG fluxes and grain yields.

2. Methods and materials

2.1. Data

We searched for peer reviewed articles and academic theses published in English or Chinese before September 2021 in Web of Science and China National Knowledge Infrastructure using the search terms ("conservation till*" OR "conservation practice" OR "no till*" OR "zero till*" OR "reduced till*" OR "minim* till*" OR "strip till*" OR "mulch till*" OR "ridge till*" OR "shallow till*" OR "vertical till*") AND ("greenhouse gas*" OR GHG OR "carbon dioxide" OR "nitric oxide" OR methane OR CO_2 OR N_2O OR CH_4 OR "soil respiration"). To be included in our database, studies must meet the following criteria: (1) field studies including paired treatments of conventional and conservation (reduced or no) tillage to assess fluxes in CO_2, N_2O, and/or CH_4; (2) fluxes in GHGs were measured across a minimum of a single entire cropping season; (3) tillage management and levels of residue retention were clearly described and there were no treatment differences in agronomic practice, such as cropping intensity, fertilization, and irrigation; and (4) means, standard deviations (SD) or standard errors (SE), and sample sizes of cumulative or mean GHG fluxes were either available or could be calculated. In addition to no tillage, strip tillage, ridge tillage, mulch tillage, minimum tillage, vertical tillage, and shallow tillage were all treated as reduced tillage and were included in our database.

Effects of potential drivers on responses of fluxes in GHGs to conservation tillage were tested by analyzing residue retention [residue retention in both conventional and conservation tillage groups (T1), residue retention only in conservation tillage group (T2), and no residue retention in conventional and conservation tillage groups (T3)]; cropland type (dryland vs. rice paddy); crop rotation (continuous vs. rotation); crop species [maize, rice, wheat, and others (including soybean, oat, pea, and barley)]; geographical coordinates; climate [mean annual temperature (MAT) and mean annual precipitation (MAP)]; soil physicochemical properties prior to conservation tillage application [pH; concentrations of C, N, nitrate (NO_3^-), ammonium (NH_4^+), phosphorus (P), available P (Olsen P), and available potassium (K); bulk density; and content of sand, silt, and clay]; experiment duration; and, where applicable, depth of standard and reduced tillage. Impacts of conservation tillage on sustainable production of global staple crops and analysis of relationships between GHG flux and grain yield responses to conservation tillage were tested by measuring total GWP (sum GWP of CO_2, N_2O, and CH_4) and yield. Data were extracted directly from main text, tables, appendices, or indirectly from figures using digitizing software (Engauge Digitizer v. 12, http://markummitchell.github.io/engauge-digitizer/). Where MAT and MAP data were not directly reported in the primary studies, they were derived from WorldClim (www.worldclim.org) at the greatest spatial resolution (30″), using geographical coordinates of the study site. After extraction and compilation, the dataset comprised 1286 paired observations from 147

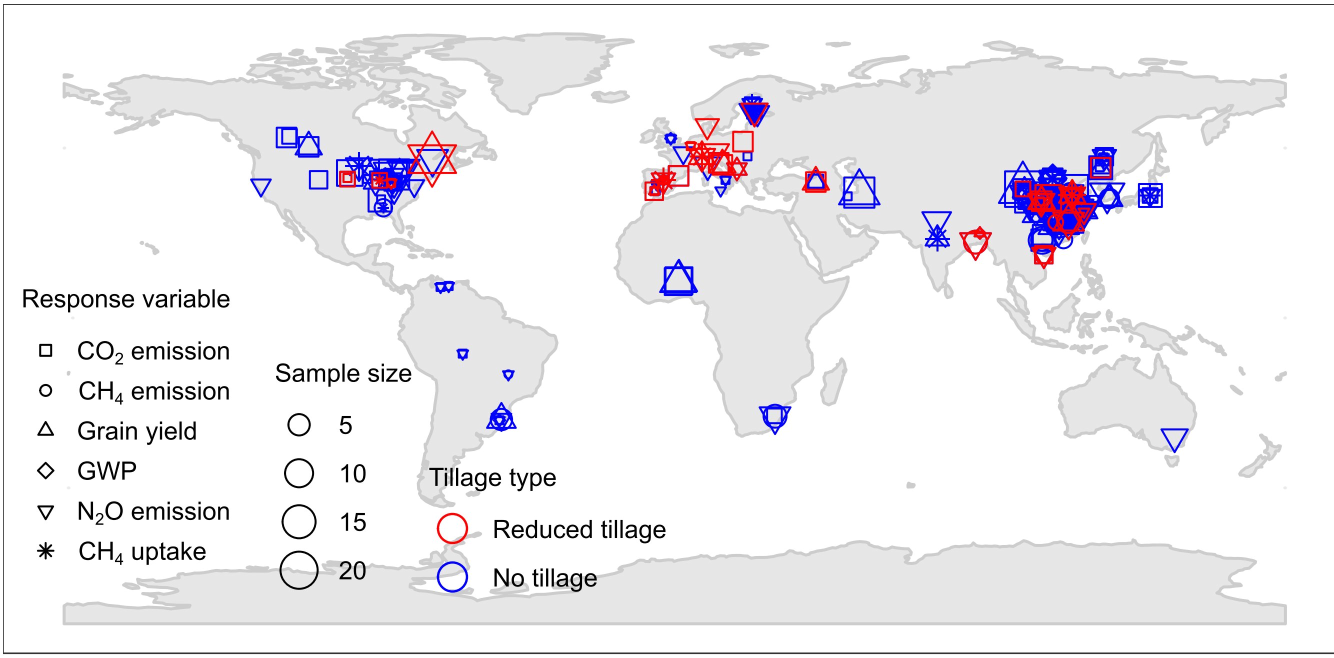

Fig. 1. Global distribution of the 1278 paired observations from 147 publications of responses of soil greenhouse gases and crop yields to conservation tillage. Shape size indicates size of paired observations. GWP: global warming potential.

independent publications (108 in English and 39 in Chinese with English abstract) (Fig. 1, Appendix 1).

2.2. Statistical analysis

Effects of conservation tillage on GHG fluxes, GWP and yield compared with conventional tillage were tested using the natural log response ratio (lnRR) as a proxy for effect size (Koricheva et al., 2013):

$$\ln RR = \ln\left(\frac{\overline{X}_t}{\overline{X}_c}\right) \tag{1}$$

where $\overline{X}_t$ and $\overline{X}_c$ are mean responses to conservation and conventional

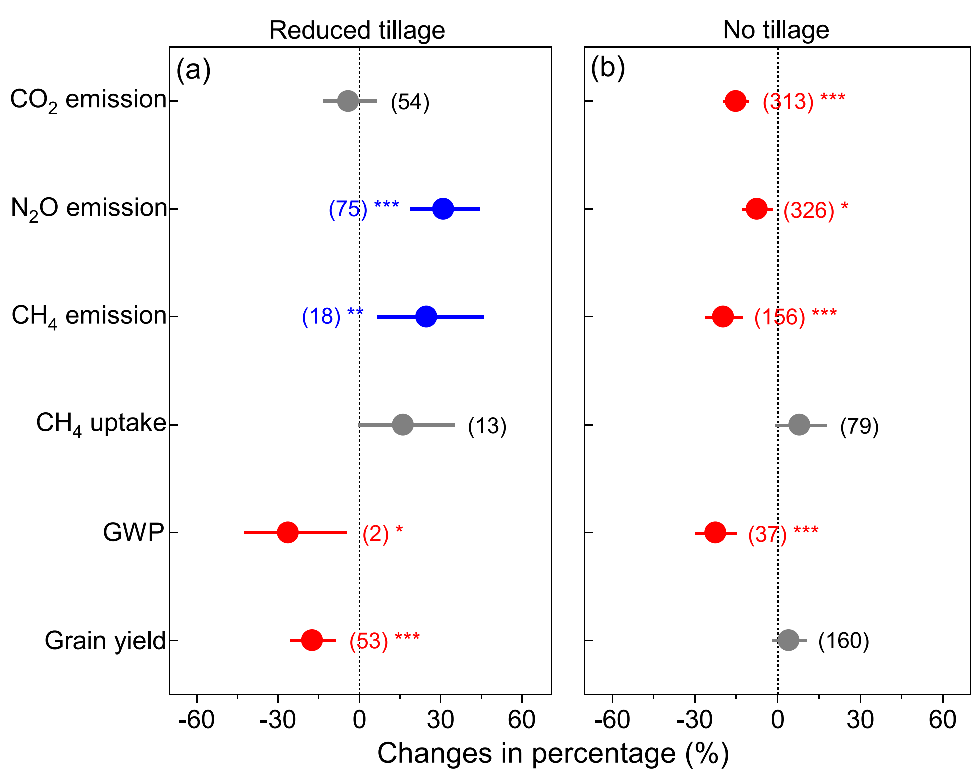

Fig. 2. Overall global effects of reduced tillage (a) and no tillage (b) on fluxes in cropland soil greenhouse gases, global warming potential (GWP), and crop yields. Data are means ± 95% confidence intervals; number of paired observations is shown in parentheses; blue and red indicate positive and negative effects, respectively, at *p < 0.05, **p < 0.01, and ***p < 0.001.

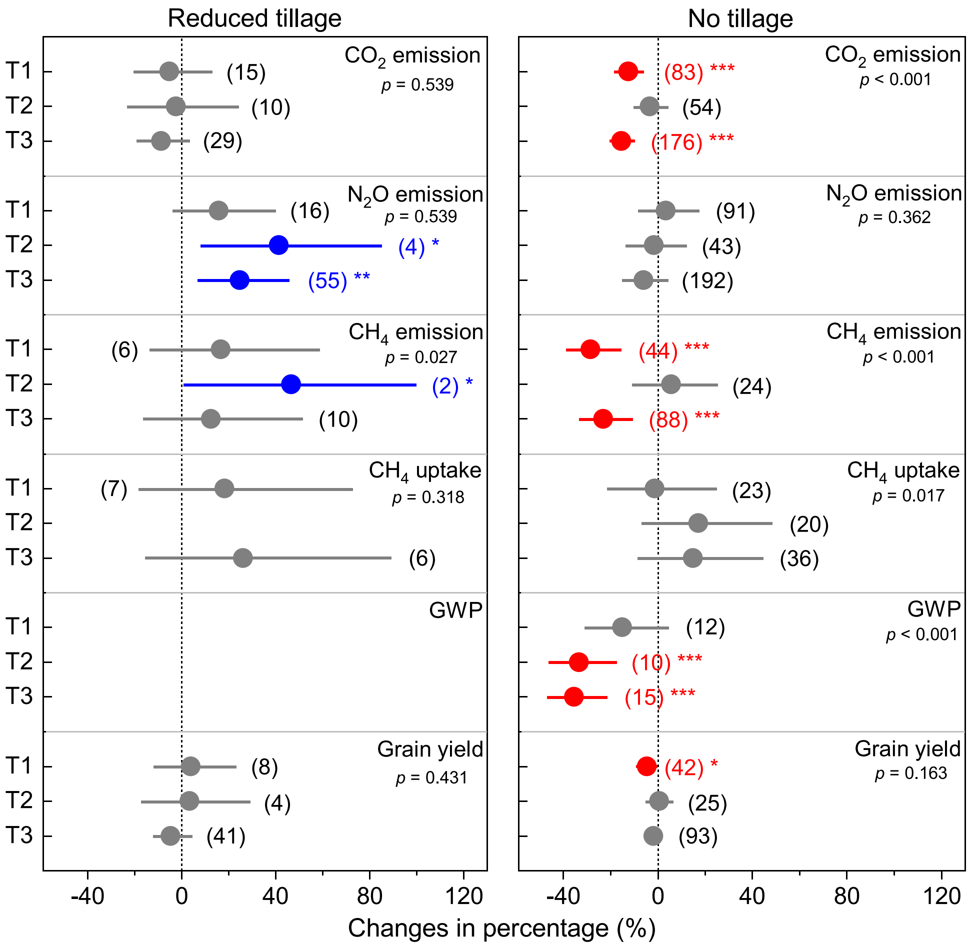

Fig. 3. Influence of crop residue retention on effects of reduced tillage (a) and no tillage (b) on soil greenhouse gases fluxes, global warming potential (GWP), and crop yields. Data are means ± 95% confidence intervals; number of paired observations is shown in parentheses; blue and red indicate positive and negative effects, respectively, at *$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$. T1: residue retention in both conventional and conservation tillage groups; T2: residue retention only in conservation tillage group; T3: no residue retention in conventional and conservation tillage groups.

tillage, respectively. Variance (v) associated with each lnRR was estimated as:

$$v = \frac{s_t^2}{n_t \overline{X}_t^2} + \frac{s_c^2}{n_c \overline{X}_c^2} \quad (2)$$

where s_t and s_c are SDs of responses to conservation and conventional tillage, respectively, and n_t and n_c are conservation and conventional tillage sample sizes, respectively. The weight for each lnRR (w) was calculated as the reciprocal of its variance (1/v).

Overall weighted effect sizes ($\ln RR_{++}$) of conservation tillage on GHG fluxes, GWP, and grain yield were calculated with an intercept-only linear mixed-effects model for each response variable, using the lme4 package in R (Bates et al., 2014). In each linear fixed-effects model, lnRR was fitted as the response variable and the identity of primary studies from which data were extracted was fitted as a random effect factor, to account for potential dependence among observations from a single primary study (Yue et al., 2021). Then, effects of potential drivers on responses of GHGs, GWP, and grain yield to conservation tillage were tested using meta-regression analysis, in which variables, which had been fitted as fixed effect factors in the linear mixed-effects model, were assessed separately, aiming to include as many data points as possible. To aid interpretation of results, $\ln RR_{++} \pm$ 95% confidence intervals (CIs) were back-transformed to proportions (%), using the equation $(e^{\ln RR_{++}} - 1) \times 100$. All the statistical analyses were performed in R version 4.1.1 (R Core Team, 2021).

3. Results

3.1. Overall effects of conservation tillage

Compared with conventional tillage, reduced tillage led to greater emissions of N_2O (31.0%) and CH_4 (24.7%), and lower GWP (26.3%) and yields of staple crops (17.4%) at the global scale; there were no effects of reduced tillage on CO_2 emissions or CH_4 uptake (Fig. 2a). In contrast, no tillage led to lower emissions of CO_2 (15.1%), N_2O (7.5%), and CH_4 (19.8%), and lower total GWP of these three GHGs compared with conventional tillage, with no effect on CH_4 uptake or crop yields (Fig. 2b).

3.2. Drivers of GHG responses to tillage practice

Crop residue retention showed limited impacts on the effects of reduced tillage on GHG fluxes, except for N_2O and CH_4 emissions, which were increased with residue input (Fig. 3a). The significantly negative effects of no tillage on CO_2 and CH_4 emissions became non-significant with residue input, but residue retention did not influence the effects of no tillage on GWP (Fig. 3b). Emissions of N_2O and CH_4 under reduced tillage were greater in dryland and rice paddies, respectively (Fig. 4a), while no tillage led to lower emissions of CO_2 and CH_4 in drylands and rice paddies, and lower crop GWP in dryland crops (Fig. 4b). Levels of N_2O emissions were greater under reduced tillage in crops cultivated in rotation (Fig. 4c) and under no tillage in continuous crops (Fig. 4d). Under no tillage management, there were lower levels of CO_2 emissions in continuous and rotated crops, N_2O in rotated crops, and CH_4 in continuous crops, and reduced CH_4 uptake in continuous crops and lower GWP in rotated crops (Fig. 4d).

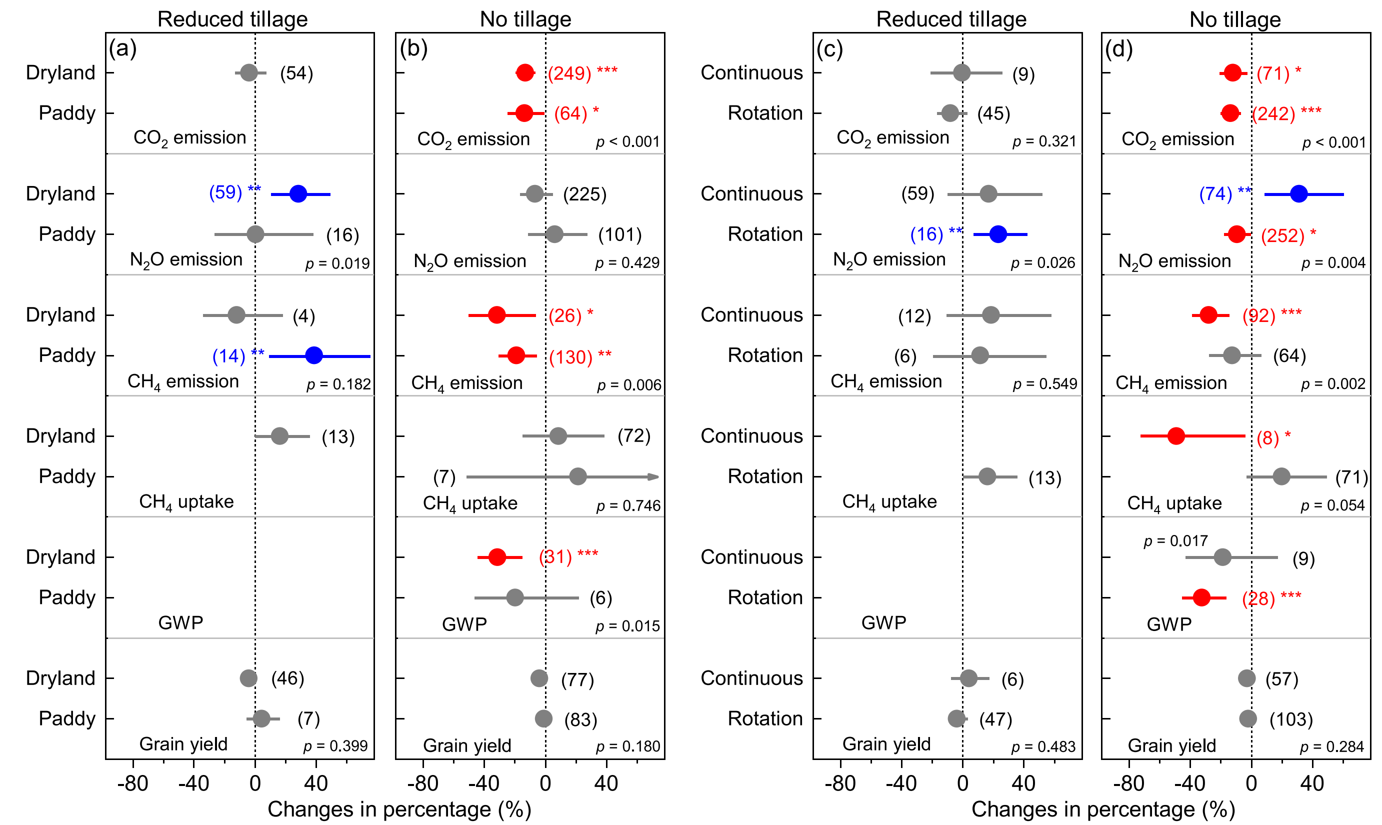

Fig. 4. Impacts of cropland type (dryland vs. rice paddy) and crop rotation regime on effects of reduced tillage and no tillage on soil greenhouse gases fluxes, global warming potential (GWP), and crop yields. Data are means ± 95% confidence intervals; number of paired observations is shown in parentheses; blue and red indicate positive and negative effects, respectively, at *p < 0.05, **p < 0.01, and ***p < 0.001.

Effects of conservation tillage on GHGs and GWP and yield of crops tended to vary with crop species, where there were greater emissions of N_2O in maize croplands and CH_4 emissions in rice paddies under reduced tillage (Fig. 5a). Under no tillage, emissions of CO_2 were lower in all crop species, while emissions of N_2O were lower in maize and those of CH_4 were lower in wheat and other crops; levels of GWP were lower in wheat and other crops and crop yields were lower in maize (Fig. 5b).

Effects of reduced tillage on CO_2 emissions were negatively related to soil bulk density and positively related to soil silt content, while effects on N_2O emissions were negatively related to MAP and positively related to soil pH and silt content (Table 1). Effects of reduced tillage on CH_4 uptake were negatively related to soil C content and reduced tillage depth, and positively related to sol bulk density and effects on crop yields were negatively related to soil pH and silt content and positively related to soil available P and sand content. Effects of no till on N_2O emissions were negatively related to MAP and positively related to soil bulk density, while effects on CH_4 uptake were negatively related to soil bulk density and silt content and positively related to soil clay content and effects on crop yield were negatively related to soil available P.

3.3. *Relationships between GHGs and grain yield in response to conservation tillage*

Using pairwise data we assessed the potential relationships between the responses of GHGs and grain yield to either reduced or no tillage. Results showed that the lnRR of grain yield showed no relationships with the lnRR of CO_2 emission, CH_4 emission, and CH_4 uptake under the treatment of neither reduced tillage nor no tillage (Fig. 6). However, the lnRR of N_2O emission to both reduced and no tillage were significantly positively correlated with the lnRR of grain yield, with a higher slop for reduced tillage compared with no tillage (Fig. 6).

4. Discussion

4.1. *Contrasting effects of reduced and no tillage*

Conservation tillage, particularly no tillage, has become an effective and widely adopted financially affordable practice to improve C sequestration and soil fertility (Alvarez et al., 2014). Although the effects of conservation tillage on soil GHGs have been reported (Abdalla et al., 2016; Huang et al., 2018; Mei et al., 2018; Shakoor et al., 2021; Zhao et al., 2016), studies have tended to focus on effects of no tillage or did not separate the effects of reduced from no tillage. Using a much larger dataset than previous meta-analyses (Abdalla et al., 2016; Maucieri et al., 2021; Shakoor et al., 2021; Zhao et al., 2016), we showed that reduced tillage has no effect on CO_2 emissions, whereas no tillage reduce CO_2 emissions by 15.1%, supporting findings from a previous meta-analysis, in which a 21% decrease was reported (Abdalla et al., 2016). These lower CO_2 emissions under no tillage management may be attributed to slower rates of organic matter decomposition, due to reduced soil aeration and breakdown of soil aggregates that restrict access to decomposers (Six et al., 2004a, 2002). Our results showed that reduced tillage did not affect CO_2 emissions, which may be attributed to that the disturbance of soils under reduced tillage did not differ from that under conventional tillage. This potential mechanism is supported by our finding that neither tillage depth nor reduced tillage depth affected the effect of reduced tillage on CO_2 emissions (Table 1).

Reduced tillage was found to stimulate emissions of N_2O and CH_4, which were both instead decreased by no tillage. Results on the effects of conservation tillage on the emissions of N_2O and CH_4 from previous meta-analyses varied substantially. For example, no tillage was found to significantly increase the emissions of both N_2O and CH_4 (Huang et al., 2018; Shakoor et al., 2021), whereas other meta-analyses found that no tillage significantly increased N_2O emission but decreased CH_4 emission

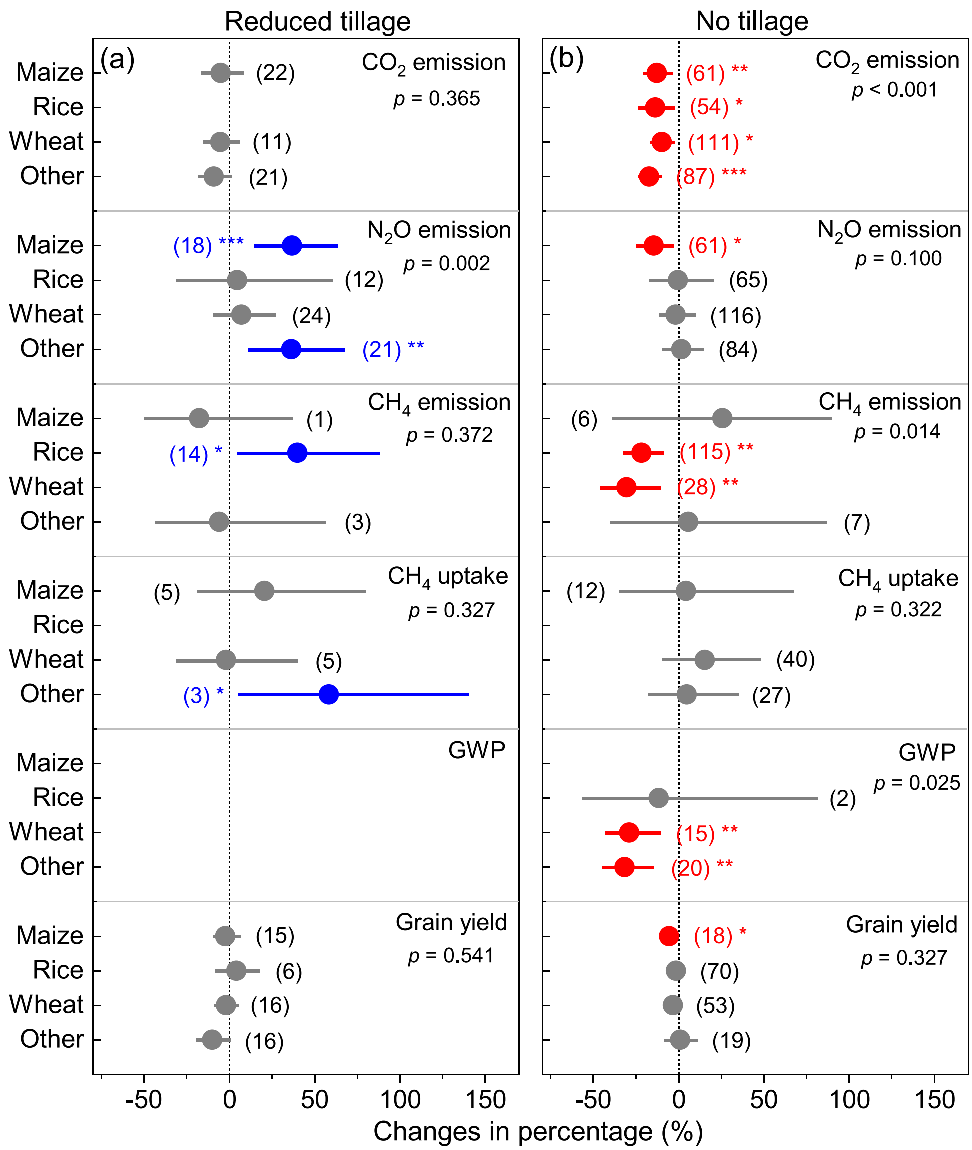

Fig. 5. Influence of crop species on effects of reduced tillage (a) and no tillage (b) on soil greenhouse gases fluxes, global warming potential (GWP), and crop yields. Data are means ± 95% confidence intervals, and number of paired observations is shown in parentheses. The other crop species include soybean, oat, pea, and barley in addition to maize, rice, and wheat. Blue and red indicate positive and negative effects, respectively, at *p < 0.05, **p < 0.01, and ***p < 0.001.

(Maucieri et al., 2021; Zhao et al., 2016). The production of N_2O is strongly controlled by soil microbial processes that influence nitrification and denitrification, which are regulated in turn by changes in soil aeration, soil water availability, soil structure, vertical distribution of organic matter, and soil temperature and moisture (Ball, 2013; Gödde and Conrad, 2000). The opposite effects of reduced and no tillage on N_2O emission may be explained by the following reasons: (1) reduced and no tillage have divergent effects on the activities and/or abundances of nitrifying and denitrifying microbial communities; (2) reduced and no tillage differently affect soil properties such as water availability; and (3) the relatively small sample size for reduced tillage compared with no tillage may have biased our results of reduced tillage effects on soil N_2O emissions.

Methane is the principal gaseous product of anaerobic decomposition of organic matter, particularly in anoxic rice paddies (Canadell and Schulze, 2014; Smith et al., 2008). The significantly positive effects of reduced tillage compared with conventional tillage on CH_4 emissions may be explained by increase in soil bulk density and water-filled pore spaces that ultimately facilitate the anaerobic decomposition of organic matter. However, a much more porous soil structure under no tillage than reduced tillage can favor CH_4 diffusion into oxidizing zones, slightly but significantly increasing CH_4 uptake and decreasing net emissions (Liu et al., 2015). This potential mechanism is further supported by our result that no tillage showed a marginally positive effect on CH_4 uptakes (Fig. 2). Despite the divergent responses of CO_2, N_2O, and CH_4 fluxes to reduced and no tillage observed here, we acknowledge the small sample size for the effects of reduced tillage that may lead to biased results, but it is possible that total GWP of these GHGs may be reduced under the two conservation tillage approaches. While our results showed a lack of effect of no tillage on crop yields, we found that reduced tillage reduces grain yield. Positive, negative, and no effects of no tillage on crop yield were all found in previous meta-analysis studies (Huang et al., 2018; Pittelkow et al., 2015; Shakoor et al., 2021), and the different results may be resulted from the divergent datasets used in these studies. The negative effects of reduced tillage on crop yield may be attributed to decreased water use efficiency of crops (Plaza-Bonilla et al., 2014a). Overall, given the positive effects of reduced tillage on emissions of GHGs, we suggest that reduced tillage may not be an appropriate conservation tillage practice in grain crops.

Table 1

Univariate linear mixed-effects model analysis of impacts of moderator variables on effect sizes (lnRR) of conservation tillage (reduced and no tillage) on fluxes in soil greenhouse gas emissions, global warming potential (GWP), and crop yields. Data in bold indicate effects at *p < 0.05, **p < 0.01, and ***p < 0.001.

Moderator variable	Reduced tillage										No tillage											
	CO_2 emission		N_2O emission		CH_4 emission		CH_4 uptake		Grain yield		CO_2 emission		N_2O emission		CH_4 emission		CH_4 uptake		GWP		Grain yield	
	Estimate	n	Estimate	n	Estimate	n	Estimate	n	Estimate	n	Estimate	n	Estimate	n	Estimate	n	Estimate	n	Estimate	n	Estimate	n
Latitude (°)	-0.029	54	0.203	75	-0.002	18	1.298	13	-0.073	53	-0.047	313	0.169	326	-0.413	156	-0.795	79	-0.606	37	-0.012	160
Altitude (m)	0.018	54	0.103	75	-0.003	18	0.300	13	0.017	53	-0.013	313	-0.007	326	-0.012	156	-0.012	79	0.056	37	0.005	160
MAT (°C)	0.133	54	0.068	75	0.020	18	0.540	13	-0.065	53	0.029	313	**-0.299****	326	0.225	156	0.330	79	-0.194	37	-0.008	160
MAP (mm)	0.039	54	**-0.378***	75	-0.114	18	-0.488	13	0.097	53	-0.011	313	-0.151	326	0.147	156	0.387	79	-0.219	37	-0.023	160
pH	0.542	38	**1.533***	41	0.343	18	3.249	10	**-0.351***	31	-0.356	171	0.003	234	-0.150	132	-0.306	39	2.878	16	-0.001	122
C ($g \cdot kg^{-1}$)	0.096	32	-0.423	33	0.202	12	**-1.467****	7	-0.017	26	-0.033	221	-0.022	229	-0.176	128	0.469	52	0.008	24	0.036	135
N ($g \cdot kg^{-1}$)	-0.118	18	-0.420	27	0.125	9	-1.429	7	0.117	21	-0.021	171	-0.076	197	0.067	113	0.385	48	0.016	20	-0.023	98
NO_3^- ($mg \cdot kg^{-1}$)			-1.455	5							-0.001	29	0.042	45	-0.075	14	0.367	13	-0.018	6	-0.112	23
NH_4^+ ($mg \cdot kg^{-1}$)			-1.698	5							0.100	30	0.168	42	-0.039	15	-2.202	13	-0.099	7	0.044	23
P ($g \cdot kg^{-1}$)	0.134	17	-0.091	13							0.143	61	-0.261	79	-0.052	59	0.446	27	0.136	13	0.003	26
Available P ($mg \cdot kg^{-1}$)			0.105	18	-0.619	8			**0.123*****	10	-0.052	65	-0.194	86	-0.170	79	1.322	9	-0.010	6	**-0.047***	83
Available K ($mg \cdot kg^{-1}$)			3.751	13	-0.823	8			-0.613	10	-0.043	47	-0.558	78	-0.053	79			-0.111	6	0.034	61
Bulk density ($g \cdot cm^{-3}$)	**-1.780****	21	-1.157	25	-1.157	25	**4.227****	7	-0.424	9	-0.937	127	**1.379****	175	1.833	42	**-3.046****	53	-4.255	27	-0.173	58
Sand (%)	-0.074	43	-0.156	54	-0.015	10	1.035	10	**0.039****	46	-0.063	122	0.085	139	-0.019	25	-0.187	27	-0.347	6	0.037	59
Silt (%)	**0.083***	43	**0.385***	54	-0.187	10	0.319	10	**-0.110***	46	0.058	122	0.122	139	-0.236	25	**-2.917*****	27	-0.455	6	0.034	59
Clay (%)	-0.058	43	-0.054	60	0.229	10	-0.445	10	-0.039	46	0.017	147	0.077	145	0.359	27	**1.187*****	27	-0.229	6	-0.027	81
Duration (year)	-0.031	54	0.008	75	-0.113	18	-0.013	13	0.008	53	0.016	313	-0.023	326	0.003	156	0.018	79	-0.152	37	-0.016	160
Tillage depth (cm)	-0.122	51	0.105	63	-0927	12	-0.685	13	-0.111	53	-0.154	219	-0.013	245	0.138	108	-0.018	64	-0.486	33	0.001	78
Reduced tillage depth (cm)	0.023	54	-0.016	66	-0.139	12	**-0.495****	13	-0.044	53												

CO_2: carbon dioxide; N_2O: nitrogen dioxide; CH_4: methane; MAT: mean annual temperature; MAP: mean annual precipitation; C: soil carbon concentration; N: soil nitrogen concentration; P: soil phosphorus concentration; K: soil potassium concentration.

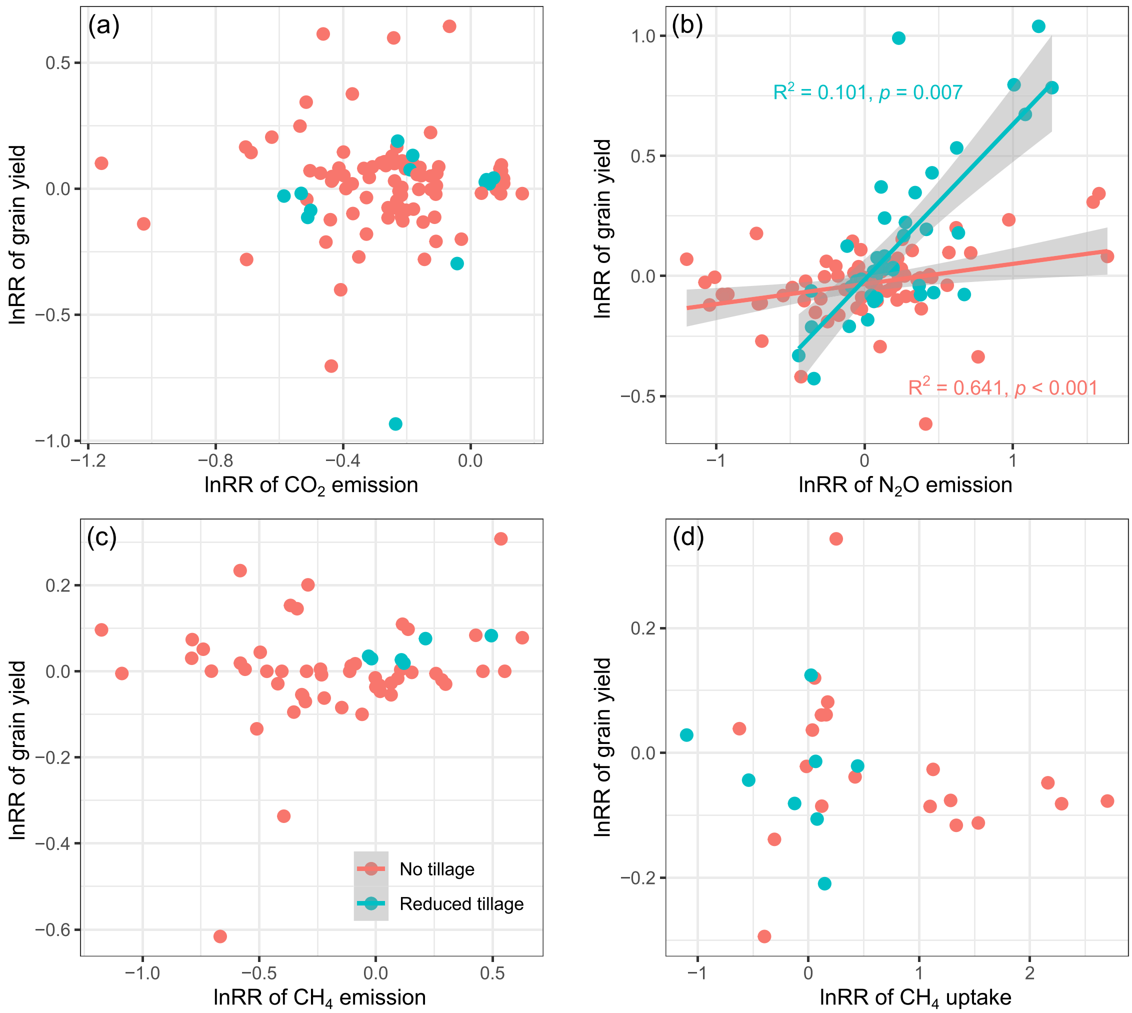

Fig. 6. Relationships between responses of crop yields and fluxes in CO_2, N_2O, and CH_4 to reduced (blue) and no (red) tillage. Responses were quantified by natural log response ratios (lnRR) and linear regressions were fitted where p < 0.05.

4.2. Varying effects of moderator variables

The influence of moderator variables, such as crop residue retention, crop rotation regime, crop species, climate, and soil physicochemical properties, were important in regulating the effects of conservation tillage on GHG fluxes. Retention of crop residues is an important factor in the regulation of soil properties, including in the reduction of soil bulk density and increase in aggregate mean weight diameter, geometric mean weight diameter, water stable aggregate, and available water capacity, that are tightly correlated with the emission of GHGs (Li et al., 2019). In our study, N_2O and CH_4 emissions were higher with residue retention under reduced tillage, and the negative effects of no tillage on CO_2 and CH_4 emissions were offset with residue inputs (Fig. 3), which are in consistent with findings from previous meta-analyses that found residue retention stimulates positive effects of reduced and no tillage on SOC stocks and N_2O emissions (Du et al., 2017; Li et al., 2019; Zhao et al., 2016). Increases in the emissions of GHGs with residue retention may be attributed to the direct addition of residue organic C and nutrients that impact soil physicochemical properties and facilitate microbial communities and activities that are directly related to the production of GHGs (Li et al., 2019; Liu et al., 2014).

Cropland type is an important driver of the effects of reduced tillage on GHG emissions, because we found emissions of N_2O and CH_4 were greater in dryland and rice paddies, respectively, under this management approach. The impacts of cropland type may be explained by that soil bulk density, compaction, and water-filled pore spaces that are closely related to the production and diffusion of CH_4 in soils varied significantly among dryland and rice paddies (Liu et al., 2015). Rotation regime is an important driver of conservation tillage effects on GHG emissions, where continuous monocultures are more likely to reduce N_2O emissions than crop species in rotation under reduced tillage, but increase N_2O emissions and decrease CH_4 uptake under no tillage; these contrasting effects of crop rotation regime on GHGs fluxes are likely to be attributed to effects on soil properties and biogeochemical processes (Behnke and Villamil, 2019; Behnke et al., 2018). Microbial activity is a key factor in the production of GHGs (Banger et al., 2012; Wang et al., 2019), and it is likely that the impacts of crop species on the effects of reduced and no tillage on GHG fluxes are attributed to differences in microbe communities and activities of soils planted with different crop species, along with contrasting nutrient use strategies and divergent effects of root traits on soil properties.

Climate can affect conservation tillage impacts on GHG fluxes (Shakoor et al., 2021); however, our results indicate limited effects of climate, with negative impacts of MAP and MAT on the effect of reduced and no tillage on N_2O emissions, respectively. Previous meta-analyses that revealed greater N_2O emissions occur in tropical and warm-temperature climate zones (Mei et al., 2018; Van Kessel et al., 2013) support our findings that higher temperatures are likely to reduce the negative effects of no tillage on N_2O emissions. While soil properties, particularly bulk density and texture, were found to drive effects of conservation of tillage on GHGs, their impacts were inconsistent and varied between conservation tillage type. For example, bulk density is directly correlated with the decomposition of soil organic matter and anaerobic condition (Smith et al., 2001, 2008), and can thus indirectly regulate fluxes in CO_2 and CH_4 under reduced and no tillage management. Likewise, sand, silt, and clay components of soil texture mediate conservation tillage effects (Pareja-Sánchez et al., 2019; Zhang et al., 2015), possibly as a result of associated variation in soil oxygen availability (Zhang et al., 2015; Zhou et al., 2014). While duration of implementation of conservation tillage has been cited as moderator of tillage effects on GHGs (Six et al., 2004b), we found no evidence for similar effects under neither reduced nor no tillage management. In addition, reduced tillage depth only had a negative effect on CH_4 uptake, indicating that greater reductions in tillage depth led to lower levels of CH_4 uptake.

4.3. Sustainable crop management for GHG reduction and greater crop yields

We assessed the relationships between responses of GHG fluxes and crop yields to reduced and no tillage managements to see if changes in GHG fluxes were correlated with crop production. Using paired data, we found that only N_2O emissions were positively related to crop yields under the two conservation tillage approaches, indicating a tradeoff between crop yield and N_2O emissions. We found a lack of effects of no tillage on crop yields, agreeing with the results from a recent meta-analysis (Shakoor et al., 2021), and an associated decrease in GHG emissions, while reduced tillage stimulates emissions of N_2O and CH_4 and decreases crop yields. Thus, overall, we suggest no tillage management is an effective approach to mitigate emissions of GHGs in eco-agriculture.

4.4. Uncertainty analysis

Despite the overall global patterns of the effects of reduced and no tillage on the fluxes of GHGs found in our study, there are still several limitations or uncertainties. First, the sample size for reduced tillage in our database is relatively low compared with that for no tillage, which may have limited our ability to fully assess its effects, as well as the associated driving factors, on soil GHG fluxes. Second, we treated strip tillage, ridge tillage, mulch tillage, and vertical/shallow tillage all as reduced tillage because of limited observations, which prevents our ability to evaluate if different types of reduced tillage have different impacts on soil GHG fluxes. Third, our data were mainly from east Asia, Europe, and North America, with limited data points from other regions of the world, which hampers to assess the effects of conservation tillage on GHG fluxes across larger scales of climate zones, soil properties, and crop species for a more robust conclusion. Therefore, we suggest that future studies should focus more on how different types of reduced tillage such as strip tillage, ridge tillage, mulch tillage, and vertical/shallow tillage on soil GHG fluxes, especially in regions with limited research such as Africa, Oceania, South America, and Russia.

5. Conclusions

Using a larger dataset than previous meta-analysis studies, results from our systematic study not only confirmed some previous findings and revealed new and important insights of effects of conservation tillage approaches on fluxes of GHGs, GWP, and crop yield. Reduced tillage stimulates emissions of N_2O and CH_4 and decreases crop yield and total GWP, with no impact on CO_2 emissions or CH_4 uptake. No tillage suppresses emissions of CO_2, N_2O, CH_4, and total GWP of these GHGs, with no effect on CH_4 uptake or crop yields. Drivers of these effects were found to include residue retention, cropland type, rotation regime, crop species, and soil physicochemical properties. Overall, our results indicate that reduced tillage stimulates emissions of GHGs and decreases crop yields, whereas no tillage management decreases GHG emissions and GWP, with no crop yield penalty. Thus, we suggest no tillage is an effective sustainable agricultural management practice for the mitigation of climate warming and provision of food security.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Raw data used in the study were deposited in figshare with a DOI (https://doi.org/10.6084/m9.figshare.21580965.v1).

Acknowledgements

K.Y. was funded by the National Natural Science Foundation of China (31922052 and 32271633), Y.P. was founded by the National Natural Science Foundation of China (32201342) and Natural Science Foundation of Fujian Province (2022J01642), F.W. was founded by the National Natural Science Foundation of China (32171641), X.N. was funded by the National Natural Science Foundation of China (32022056), and J.P. was funded by the Spanish Ministry of Science (grant PID2019–110521 GB-I00), the Catalan government grant SGR2017–1005, and the Fundación Ramón Areces grant ELEMENTAL-CLIMATE.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2023.105643.

References

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. Biogeosciences 13, 3619–3633.
Alvarez, C., Alvarez, C.R., Costantini, A., Basanta, M., 2014. Carbon and nitrogen sequestration in soils under different management in the semi-arid Pampa (Argentina). Soil Tillage Res. 142, 25–31.
Ball, B., 2013. Soil structure and greenhouse gas emissions: a synthesis of 20 years of experimentation. Eur. J. Soil Sci. 64, 357–373.
Banger, K., Tian, H., Lu, C., 2012. Do nitrogen fertilizers stimulate or inhibit methane emissions from rice fields? Glob. Change Biol. 18, 3259–3267.
Bates, D., Mächler, M., Bolker, B., Walker, S., 2014. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67, 1–48.
Bayer, C., Gomes, J., Vieira, F.C.B., Zanatta, J.A., de Cássia Piccolo, M., Dieckow, J., 2012. Methane emission from soil under long-term no-till cropping systems. Soil Tillage Res. 124, 1–7.
Behnke, G.D., Villamil, M.B., 2019. Cover crop rotations affect greenhouse gas emissions and crop production in Illinois, USA. Field Crops Res. 241, 107580.
Behnke, G.D., Zuber, S.M., Pittelkow, C.M., Nafziger, E.D., Villamil, M.B., 2018. Long-term crop rotation and tillage effects on soil greenhouse gas emissions and crop production in Illinois, USA. Agric., Ecosyst. Environ. 261, 62–70.
Canadell, J.G., Schulze, E.D., 2014. Global potential of biospheric carbon management for climate mitigation. Nat. Commun. 5, 1–12.
Chen, H., Li, X., Hu, F., Shi, W., 2013. Soil nitrous oxide emissions following crop residue addition: a meta-analysis. Glob. Change Biol. 19, 2956–2964.
Du, Z., Angers, D.A., Ren, T., Zhang, Q., Li, G., 2017. The effect of no-till on organic C storage in Chinese soils should not be overemphasized: A meta-analysis. Agric., Ecosyst. Environ. 236, 1–11.
FAO, 2011. Save and Grow. A policymaker's guide to the sustainable intensification of smallholder crop production, Rome, Italy.
FAO, 2014. FAOStat: Food and Agriculture Organization of the United Nations-Statistics Division.
Gödde, M., Conrad, R., 2000. Influence of soil properties on the turnover of nitric oxide and nitrous oxide by nitrification and denitrification at constant temperature and moisture. Biol. Fertil. Soils 32, 120–128.
He, J., Li, H., Rasaily, R.G., Wang, Q., Cai, G., Su, Y., Qiao, X., Liu, L., 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.
Huang, Y., Ren, W., Wang, L., Hui, D., Grove, J.H., Yang, X., Tao, B., Goff, B., 2018. Greenhouse gas emissions and crop yield in no-tillage systems: A meta-analysis. Agric., Ecosyst. Environ. 268, 144–153.

IPCC, 2014. Climate Change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.
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, 34–40.
Koricheva, J., Gurevitch, J., Mengersen, K., 2013. Handbook of meta-analysis in ecology and evolution. Princeton University Press, Princeton and Oxford.
Li, Y., Li, Z., Cui, S., Jagadamma, S., Zhang, Q., 2019. Residue retention and minimum tillage improve physical environment of the soil in croplands: A global meta-analysis. Soil Tillage Res. 194, 104292.
Lipper, L., Thornton, P., Campbell, B.M., Baedeker, T., Braimoh, A., Bwalya, M., Caron, P., Cattaneo, A., Garrity, D., Henry, K., 2014. Climate-smart agriculture for food security. Nat. Clim. Change 4, 1068–1072.
Liu, C., Lu, M., Cui, J., Li, B., Fang, C., 2014. Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. Glob. Change Biol. 20, 1366–1381.
Liu, S., Zhao, C., Zhang, Y., Hu, Z., Wang, C., Zong, Y., Zhang, L., Zou, J., 2015. Annual net greenhouse gas balance in a halophyte (Helianthus tuberosus) bioenergy cropping system under various soil practices in Southeast China. Glob. Change Biol. 7, 690–703.
Mangalassery, S., Sjögersten, S., Sparkes, D.L., Sturrock, C.J., Craigon, J., Mooney, S.J., 2014. To what extent can zero tillage lead to a reduction in greenhouse gas emissions from temperate soils? Sci. Rep. 4, 1–8.
Maucieri, C., Tolomio, M., McDaniel, M.D., Zhang, Y., Robatjazi, J., Borin, M., 2021. No-tillage effects on soil CH4 fluxes: A meta-analysis. Soil Tillage Res. 212, 105042.
Mei, K., Wang, Z., Huang, H., Zhang, C., Shang, X., Dahlgren, R.A., Zhang, M., Xia, F., 2018. Stimulation of N_2O emission by conservation tillage management in agricultural lands: A meta-analysis. Soil Tillage Res. 182, 86–93.
Pareja-Sánchez, E., Cantero-Martínez, C., Álvaro-Fuentes, J., Plaza-Bonilla, D., 2019. Tillage and nitrogen fertilization in irrigated maize: key practices to reduce soil CO_2 and CH4 emissions. Soil Tillage Res. 191, 29–36.
Pelster, D.E., Chantigny, M.H., Rochette, P., Angers, D.A., Rieux, C., Vanasse, A., 2012. Nitrous oxide emissions respond differently to mineral and organic nitrogen sources in contrasting soil types. J. Environ. Qual. 41, 427–435.
Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X., van Groenigen, K.J., Lee, J., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 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.L., 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.L., 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.
R Core Team, 2021. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.
Reicosky, D., 1997. Tillage-induced CO_2 emission from soil. Nutr. Cycl. Agroecosystems 49, 273–285.
Saunois, M., Bousquet, P., Poulter, B., Peregon, A., Ciais, P., Canadell, J.G., Dlugokencky, E.J., Etiope, G., Bastviken, D., Houweling, S., Janssens-Maenhout, G., Tubiello, F.N., Castaldi, S., Jackson, R.B., Alexe, M., Arora, V.K., Beerling, D.J., Bergamaschi, P., Blake, D.R., Brailsford, G., Brovkin, V., Bruhwiler, L., Crevoisier, C., Crill, P., Covey, K., Curry, C., Frankenberg, C., Gedney, N., Höglund-Isaksson, L., Ishizawa, M., Ito, A., Joos, F., Kim, H.S., Kleinen, T., Krummel, P., Lamarque, J.F., Langenfelds, R., Locatelli, R., Machida, T., Maksyutov, S., McDonald, K.C., Marshall, J., Melton, J.R., Morino, I., Naik, V., O'Doherty, S., Parmentier, F.J.W., Patra, P.K., Peng, C., Peng, S., Peters, G.P., Pison, I., Prigent, C., Prinn, R., Ramonet, M., Riley, W.J., Saito, M., Santini, M., Schroeder, R., Simpson, I.J., Spahni, R., Steele, P., Takizawa, A., Thornton, B.F., Tian, H., Tohjima, Y., Viovy, N., Voulgarakis, A., van Weele, M., van der Werf, G.R., Weiss, R., Wiedinmyer, C., Wilton, D.J., Wiltshire, A., Worthy, D., Wunch, D., Xu, X., Yoshida, Y., Zhang, B., Zhang, Z., Zhu, Q., 2016. . The global methane budget 2000–2012. Earth Syst. Sci. Data 8, 697–751.
Shakoor, A., Shahbaz, M., Farooq, T.H., Sahar, N.E., Shahzad, S.M., Altaf, M.M., Ashraf, M., 2021. A global meta-analysis of greenhouse gases emission and crop yield under no-tillage as compared to conventional tillage. Sci. Total Environ. 750, 142299.
Singh, B.P., Setia, R., Wiesmeier, M., Kunhikrishnan, A., 2018. Agricultural management practices and soil organic carbon storage. Soil carbon storage. Elsevier, pp. 207–244.
Six, J., Conant, R.T., Paul, E.A., Paustian, K., 2002. Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. Plant Soil 241, 155–176.
Six, J., Bossuyt, H., Degryze, S., Denef, K., 2004a. A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. Soil Tillage Res. 79, 7–31.
Six, J., Ogle, S.M., Jay Breidt, F., Conant, R.T., Mosier, A.R., Paustian, K., 2004b. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. Glob. Change Biol. 10, 155–160.
Smith, K., Conen, F., 2004. Impacts of land management on fluxes of trace greenhouse gases. Soil Use Manag. 20, 255–263.
Smith, P., Goulding, K.W., Smith, K.A., Powlson, D.S., Smith, J.U., Falloon, P., Coleman, K., 2001. Enhancing the carbon sink in European agricultural soils: including trace gas fluxes in estimates of carbon mitigation potential. Nutr. Cycl. Agroecosyst. 60, 237–252.
Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., 2008. Greenhouse gas mitigation in agriculture. Philos. Trans. R. Soc. B: Biol. Sci. 363, 789–813.
Unger, P.W., McCalla, T., 1980. Conservation tillage systems. Adv. Agron. 33, 1–58.
Ussiri, D.A., Lal, R., 2009. Long-term tillage effects on soil carbon storage and carbon dioxide emissions in continuous corn cropping system from an alfisol in Ohio. Soil Tillage Res. 104, 39–47.
Van Kessel, C., Venterea, R., Six, J., Adviento-Borbe, M.A., Linquist, B., van Groenigen, K. J., 2013. Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: a meta-analysis. Glob. Change Biol. 19, 33–44.
Wang, W., Yang, M., Shen, P., Zhang, R., Qin, X., Han, J., Li, Y., Wen, X., Liao, Y., 2019. Conservation tillage reduces nitrous oxide emissions by regulating functional genes for ammonia oxidation and denitrification in a winter wheat ecosystem. Soil Tillage Res. 194, 104347.
Weitz, A.M., Linder, E., Frolking, S., Crill, P., Keller, M., 2001. N_2O emissions from humid tropical agricultural soils: effects of soil moisture, texture and nitrogen availability. Soil Biol. Biochem. 33, 1077–1093.
West, T.O., Post, W.M., 2002. Soil organic carbon sequestration rates by tillage and crop rotation: a global data analysis. Soil Sci. Soc. Am. J. 66, 1930–1946.
Yue, K., Fornara, D.A., Li, W., Ni, X., Peng, Y., Liao, S., Tan, S., Wang, D., Wu, F., Yang, Y., 2021. Nitrogen addition affects plant biomass allocation but not allometric relationships among different organs across the globe. J. Plant Ecol. 14, 361–371.
Zhang, H.-L., Bai, X.-L., Xue, J.-F., Chen, Z.-D., Tang, H.-M., Chen, F., 2013. Emissions of CH_4 and N_2O under different tillage systems from double-cropped paddy fields in Southern China. PLoS One 8, e65277.
Zhang, Z., Guo, L., Liu, T., Li, C., Cao, C., 2015. Effects of tillage practices and straw returning methods on greenhouse gas emissions and net ecosystem economic budget in rice–wheat cropping systems in central China. Atmos. Environ. 122, 636–644.
Zhao, X., Zhang, R., Xue, J.-F., Pu, C., Zhang, X.-Q., Liu, S.-L., Chen, F., Lal, R., Zhang, H.-L., 2015. Management-induced changes to soil organic carbon in China: a meta-analysis. Adv. Agron. 134, 1–50.
Zhao, X., Liu, S.L., Pu, C., Zhang, X.Q., Xue, J.F., Zhang, R., Wang, Y.Q., Lal, R., Zhang, H. L., Chen, F., 2016. Methane and nitrous oxide emissions under no-till farming in China: a meta-analysis. Glob. Change Biol. 22, 1372–1384.
Zhou, M., Zhu, B., Brüggemann, N., Bergmann, J., Wang, Y., Butterbach-Bahl, K., 2014. N_2O and CH_4 emissions, and NO_3 leaching on a crop-yield basis from a subtropical rain-fed wheat–maize rotation in response to different types of nitrogen fertilizer. Ecosystems 17, 286–301.