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Benefits and Trade-Offs of Tillage Management in China: A Meta-Analysis

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Abstract: In China, deep tillage (DT; to >20 cm soil depth) has increased crop yields by improving soil properties, while no-tillage (NT) has been recommended to reduce the labor and machinery costs. Local farmers are willing to adopted rotary tillage (RT; harrowing to 10–15 cm depth) for easy management. However, the effects of these tillage management methods on agronomic productivity, greenhouse gas (GHG) emissions, soil organic carbon (SOC) sequestration, and economic return have not been quantified systematically, and their effectiveness remains in question. Here, we present a meta-analysis of the effects of these methods using 665 paired measurements from 144 peer-reviewed studies. The results indicated that DT significantly increased crop yields by 7.5% relative to RT, and even greater increases were observed in regions with low temperatures and with a wheat cropping system. In contrast, NT resulted in a yield reduction of 3.7% relative to RT, however, controlling for the appropriate temperature and long extension duration (>15 yr) could reduce yield losses and even increase the yield. Both DT and NT significantly enhanced SOC sequestration relative to RT. Adoption of DT would lead to both higher total GHG emissions (N_2O and CH_4) and increased energy costs, while NT reduced GHG emissions. DT management exhibited a positive net profit for all cropping systems; NT decreased the net profit for rice and wheat but increased the profit for maize. Our study highlighted the agronomic, environmental, and economic benefits and trade-offs for the different tillage methods and should enable investors and policymakers to ensure the best tillage management decisions are made depending on the location-specific conditions.

Keywords: crop yield; greenhouse gas emissions; trade-off analysis

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1. Introduction

Agriculture faces many challenges to sustainably feed a growing population by increasing yields while mitigating climate change [1,2]. Soil management is at the heart of these challenges because resilient and productive soils are necessary to sustainably intensify agriculture [3,4]. Reasonable tillage management can effectively improve the soil quality and agricultural sustainability, serving to conserve and regenerate productive soil. Although the effects of tillage management on crop yield depend on localized climate and soil conditions, it is meaningful to evaluate the yield effects at the regional or national scale [5–8]. Meanwhile, integrated assessments of tillage alternatives in terms of their ability to mitigate climate change and sequester soil carbon (SOC), are lacking [9–12]. This relationship must be quantified to set a general framework for how soil management could potentially contribute to sustainable intensification goals while achieving food security and mitigating climate change.

China has a long history of implementing tillage management to achieve high yields [13]. Deep tillage (DT), with a tillage depth of >20 cm, can relieve soil compaction, improve root proliferation, and thereby increase crop yields [14,15]. However, DT promotes the activity of soil microbes, which may increase the emission of greenhouse gases, such as nitrous oxide (N_2O) and methane (CH_4) [16,17]. No-tillage (NT) management does not disturb the soil and retains at least 30% of crop residues on the soil surface, which increases its water retention potential, reduces cost, increases efficiency, and reduces soil erosion [18–20]. Rotary tillage (RT) generally uses a cultivation depth of <20 cm; it has the advantage of being convenient in terms of mechanical equipment, it ensures good quality of the cultivated land, and has a low power requirement. In practice, RT has been widely-adopted and has spread quickly across China due to being easy to manage with low costs, and especially in the paddy fields of South China, the proportion of rotary tillage is more than 80% [16,21,22]. Current research has focused on the difference between conventional DT and NT practices [23–25]. We compared deep tillage and no tillage with rotary tillage and analyzed their benefits and trade-off effects, hoping to recognize promising alternatives, which is essential for local producers and policymakers.

In general, DT increased crop yield while NT decreased yield relative to conventional RT [16,26]. However, their relationship to yield is highly influenced by climate conditions, soil properties, and soil management practices [8,23], and the effect may even be reversed under different environmental conditions and management plans [6,8,23]. For example, because DT increased the temperature of arable land, it tended to result in higher yield, especially at relatively low temperatures [21,27]. Long-term NT management combined with straw returning is conductive to promoting the soil fertility, water conservation, and the microbial activity of rhizosphere soil [8,28,29], thereby maintaining or even increasing crop yield following an extended duration of NT. These inconsistent results highlight the importance of developing a mathematical understanding of how yield responses to tillage management plants are influenced by environment and management systems, and this can be used to protect and manage our soil and crop production.

The magnitude and direction of climate change mitigation vary due to the highly variable effects of tillage management plans on SOC changes and soil GHG fluxes. DT-induced increases in crop biomass can result in greater crop residue return to the soil, but intensive soil disturbance might increase SOC losses from stimulated decomposition [30,31]. Meanwhile, deep plowing may increase the SOC compared with NT, possibly due to soil mixing and turning the residue over onto the topsoil [16]. Some have suggested that soil N_2O emissions are expected to be greater with NT compared to conventional DT due to soil compaction and the higher soil moisture content [23,25], while others predict fewer emissions under NT owing to reduced soil temperatures and limited soil microbial activities [32,33]. Also, GHG emissions of the fuel used for tillage should be considered because NT and RT practices significantly reduce fuel consumption [10].

Profitability is important when it comes to evaluating the impact of various tillage practices. The yield change brought about by alternative tillage practices represents an important economic factor [34]. Meanwhile, labor and machine expenses for intensive tillage account for a high share of the agricultural costs [34]. For example, the yield response could be offset or exacerbated by changes in the soil, and for different crops; NT treatment provided a higher net benefit than DT for maize production [10]. Recently, the global warming cost and impacts of GHG emissions in terms of their harmful effects on the environment and human health were also added into the equation of the economic benefits [20,35]. Thus, a comprehensive trade-off analysis should examine the most economical and appropriate tillage strategy for sustainable intensification.

This study aims to address the limits and uncertainties of our current understanding of the effects of tillage on agronomic productivity, climate change mitigation, and economic return as a function of climate conditions, soil properties, and soil management. Based on data compiled from the literature, we employed a meta-analytical method to investigate variation in yield, GHG emissions, and SOC resulting from different tillage implementation plans, hoping to clarify the trade-offs or co-benefits of agronomic, economic, and environmental benefits under various tillage treatments. Based on the above research objective, our investigation was comprised of three steps. First, we regarded the RT as the control and compared it with DT and NT. Second, we explored crop yield changes induced by tillage under different climatic conditions, soil properties and management plans. Third, we investigated the extent to which climate change mitigation causes changes in SOC, GHG emissions, and energy consumption. Our assessment will help to determine whether a tillage method can achieve sustainable development by increasing yields while mitigating climate change.

2. Materials and Methods

2.1. Database Compilation

We conducted a comprehensive literature review to search for peer-reviewed publications that reported the effects of tillage management on yield, SOC sequestration, and GHG emissions prior to November 2018. We selected wheat, maize, and rice as our research objects. Wheat, maize, and rice are important cereal crops in China, accounting for 56% of China's arable land and 58% of the total plant protein in China [36]. Besides, the availability of data also limits the analysis for other crops, as the tillage managements of other crops are relatively simple in China. All data were derived from publications found by searching for keywords ('tillage management', 'deep tillage', 'no-tillage', 'rotary tillage', 'yield', and 'GHG emission') in the Web of Science database and the China Knowledge Resource Integrated Database. The literature needed to satisfy the following criteria: (a) only field experiments associated with three cereal crops (wheat, maize, rice) were included in this study; (b) experiments contained at least two different tillage management plans, including RT as the control; and (c) crop yield, SOC sequestration, or cumulative GHG emission during the crop growth period had to be explicitly reported with the published data. If the data were presented in a graph, the data were digitized using Get Data Graph Digitizer software. Publications amounting to 144 in number were included in our database, and the time period of the literature was from 1999 to 2018, mainly published in the 2010s (meta-analysis references were available in the Supplementary Materials). In total, 551 comparisons for yield, 213 comparisons for SOC sequestration, and 153 comparisons for GHG emissions derived from 144 publications were selected from the databases. The following details were also compiled from the selected publications: location (longitude/latitude), climatic conditions (annual mean temperature and precipitation), soil properties (soil bulk density, SOC, and available N), N application rate, tillage duration, yield components [spike numbers (for wheat and rice) or cob numbers (for maize), grain numbers per spike (wheat and rice) or cob (maize), and thousand kernel weight] and experimental treatments [crop types, available agronomic traits, and straw return (SR)].

2.2. Data Analyses

We conducted a random-effect meta-analysis to assess the variable effects by comparing the results of tillage management treatments and the controls using the following equation:

$$\ln R = \ln(X_t/X_c) = \ln(X_t) - \ln(X_c) \quad (1)$$

where ln R is the effect size calculated as the natural log of the response ratio for each comparison, X_t is the mean value of the variable (e.g., yield, GHG emission, and SOC sequestration) in DT or NT treatments, and X_c is the mean value of the variable in RT treatments. Log-transformation of the response ratio was carried out to stabilize the variance. Its variance (v) is estimated as:

$$v = S_t^2/n_tX_t^2 + S_c^2/n_cX_c^2 \quad (2)$$

where n_t and n_c are the sample sizes for treatments and controls, respectively, and S_t and S_c are the standard deviation for the treatment and control groups, respectively. The effect size of each observation was weighted by the inverse of the variance. Resampling procedures [bootstrap (n = 4999)] were used to generate the mean effect and 95% confidence intervals (CIs) for each grouping category. Mean effect sizes of treatment were considered significantly different from those of the control if the 95% CIs did not overlap with zero, while the effects for which the 95% CIs overlapped with zero were not significant. To improve the explanatory power, the mean effect size was transformed back to the percentage change for the DT or NT management plans relative to the RT practice and computed as:

$$(e^{\ln R} - 1) \times 100\% \tag{3}$$

A nonparametric smooth regression was fitted for the continuous variables based on a Gaussian process model. Shaded bands indicate 95% CIs, which can be considered significantly positive or negative if the 95% CIs do not overlap with zero. The meta-analysis and Gaussian process models were implemented using R software (version 3.6).

2.3. Economic and Environmental Estimate

The estimated benefits for grain yield and net profit were calculated using the following Equations (4)–(6):

$$Y_R = Y_T - Y_{CK} \tag{4}$$

$$Y_P = Y_R \times C_{price} \tag{5}$$

$$P_N = Y_P - C_T - C_{GW} \tag{6}$$

where Y_T is the crop yield of tillage treatment (DT or NT; kg ha^{-1}), Y_{CK} is the crop yield of RT (kg ha^{-1}), Y_R is the relative crop yield (kg ha^{-1}), Y_P represents the yield profit [Chinese yuan (CNY) ha^{-1}], C_{price} represents the price of cereal crops (maize, wheat, and rice prices are 2.2, 2.4, and 2.8 CNY kg^{-1}, respectively; National Compilation of Cost-benefit Data of Agricultural Products, 2015), and P_N represents the net profit (CNY ha^{-1}). C_T and C_{GW} represent the relative tillage cost and global warming cost (subtracting the cost of the tillage treatment from the RT; CNY ha^{-1}), respectively; the C_T parameters were based on the published literature, and the parameters are listed in Table 1. The cost of global warming is defined here as the cost caused by nitrous oxide and methane emissions from different tillage managements, and we calculated the global warming cost according to the market price of CO_2 for 2008, which closed at 169.36 CNY per ton, based on the published literature [20].

We calculated and estimated the total GHG emissions (kg CO_2-eq ha^{-1}) based on the emissions of N_2O and CH_4, SOC sequestration, and machine fuel consumption produced by different tillage management practices, and the functions are listed as Equations (7)–(9):

$$\text{GHG } (CH_4) = \text{CE } (CH_4) \times 25 \tag{7}$$

$$\text{GHG } (N_2O) = \text{CE } (N_2O) \times 298 \tag{8}$$

$$\triangle\text{GHG} = \text{GHG } (CH_4) + \text{GHG } (N_2O) + \text{GHG}_{\text{ tillage}} \tag{9}$$

where CE (GHG) is the cumulative GHG (kg ha^{-1}) emissions; we used the Intergovernmental Panel on Climate Change (IPCC) factors (25 for CH_4 and 298 for N_2O) to calculate the GHG emissions (kg CO_2-eq ha^{-1}) [37]. GHG $_{\text{tillage}}$ represents the GHG emission due to machine fuel consumption. We calculated GHG $_{\text{tillage}}$ based on data from the published literature, and the parameters are listed in Table 1. The $\triangle$GHG (kg CO_2-eq ha^{-1}) represents the total GHG emissions.

Table 1. Relative costs and GHG emissions of tillage methods. Relative tillage costs (CNY ha^{-1}) and GHG emissions (kg CO_2-eq ha^{-1}) for DT and NT compared to RT. Values were obtained from the cited literature. GHG, greenhouse gas; CNY, Chinese yuan; DT, deep tillage; NT, no tillage; RT, rotary tillage.

	Relative Cost by Tillage Methods		
	DT (CNY ha^{-1})	NT (CNY ha^{-1})	References
	0	−600	[38]
	225	/	[39]
	/	−195	[40]
	/	−450	[41]
	/	−375	[42]
	/	−358	[43]
	150	−600	[44]
	375	−270	[45]
Average	188	−407	
	Relative GHG Emissions by Tillage Methods		
	DT (kg CO_2-eq ha^{-1})	NT (kg CO_2-eq ha^{-1})	References
	200	−176	[46]
	288	−127	[47]
	−29	−104	[17]
	18	/	[48]
	68	−53	[49]
	8	/	[50]
	/	−171	[10]
Average	92	−126	

3. Results

3.1. Tillage Impacts on Crop Yields under Different Environments

On average, DT increased yields by 7.5% (n = 285), while NT reduced yields by 3.7% (n = 266), which differed significantly from RT (Figure 1). The low yield for NT contributed significantly to an average 3.6% reduction in spike or cob numbers, but there were no significant effects for grain number or thousand kernel weight (TKW). DT significantly increased spike or cob numbers and the number of grains per spike or cob (3.0% and 5.1%, respectively); DT also partially increased the TKW, although the effect was not significant (Figure 1). Meanwhile, the crop leaf area index (LAI) was significantly increased with DT but decreased with NT. There was no significant difference in plant height and emergence rate between the different tillage practices (Figure 1).

Based on the available data, average precipitation, and temperature, SOC, tillage duration, crop category, and SR were effective predictors of the impacts of tillage on crop yield (Figure 2). The increased yield observed for DT relative to RT showed a downward trend with increased annual precipitation (Figure 2a) and also decreased significantly with a rise in temperature (Figure 2b). The largest increase in crop production occurred under relatively low annual temperatures. The SOC stock exhibited an optimal level for increased crop production under DT, and this increase remained stable or was reduced only slightly when continuous DT was implemented for cereal crops (Figure 2c,d). Positive and significant yield effects were detected for different cereal crops under DT, and the effects were significantly higher in wheat than in rice (Figure 2e).

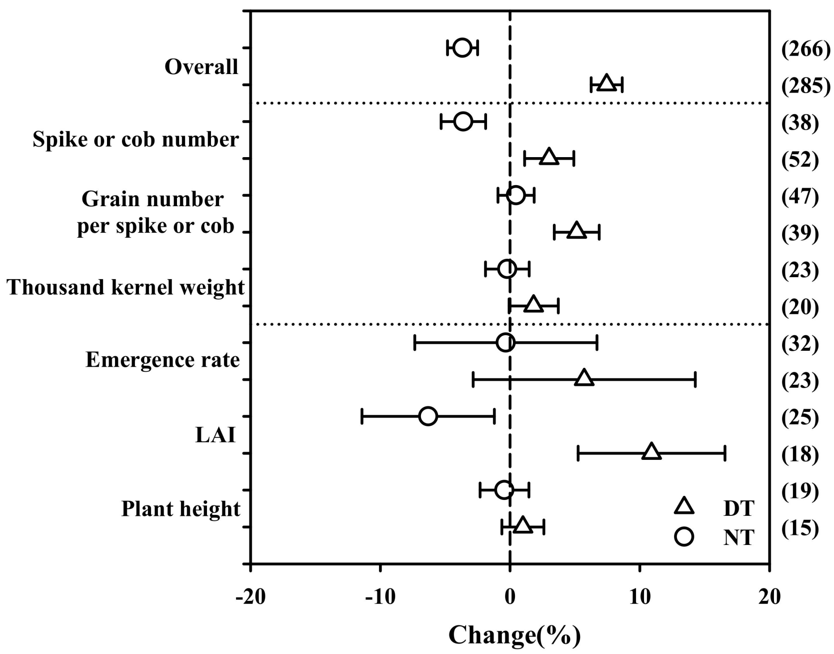

Figure 1. Changes in crop yields and agronomic traits under DT and NT compared to RT management plans. Triangles and circles indicate the effect size of DT and NT, respectively. The number of observations (n) for each category is shown in parentheses. Error bars represent 95% confidence intervals (CIs). Differences are considered significant when the CIs do not include zero. LAI: leaf area index; DT, deep tillage; NT, no tillage; RT, rotary tillage.

NT showed a reduction in yield with increased precipitation; however, there was a lower yield reduction, or even no yield loss, at moderate temperatures (Figure 2g,h). Similar to DT management plans, higher yield was detected in response to an optimal SOC content (Figure 2i). Continuous adoption of NT reduced the negative effects on crop yields and even increased yield when NT was carried out for >15 years (Figure 2j). The application of NT in paddy fields resulted in a significant yield reduction compared with wheat and maize (Figure 2k). The application of SR did not change the yield response to tillage when compared with no SR (NSR; Figure 2f,l).

3.2. Effects on Soil Carbon Sequestration and GHG Emission

In general, despite a large variation in the basic SOC content, DT and NT management plans both had significant and positive effects on SOC sequestration relative to RT. DT significantly increased SOC sequestration by 5.8% (n = 29, p < 0.05) and NT increased SOC sequestration by 5.2% (n = 43, p < 0.01) compared to RT (Figure 3A). The storage of SOC changed with tillage and cropping duration, and there were increases in SOC storage under DT and NT of 0.35 and 0.87 Mg C ha^{-1} per season, respectively (Figure 3B). Due to the differences in soil disturbance, DT significantly reduced soil bulk density by 3.9%, and NT increased the bulk density by 4.4%. No significant differences were detected for soil-available N (Figure 3A).

Both CH_4 and N_2O are important contributors to GHG emissions and varied according to the cropping systems used. For the upland crops, DT significantly increased N_2O emissions by 15.1% relative to RT (n = 32; Figure 4). In paddy fields, DT increased N_2O and CH_4 emissions by 7.3% and 6.6%, respectively, but the effects were not significant. NT reduced N_2O emission by 3.2% and 6.0% for upland crops and rice, respectively, and reduced CH_4 emission by 7.4% in the paddy fields. CH_4 tends to be absorbed in dry land; DT promoted CH_4 absorption by 5.0%, and NT reduced CH_4 absorption by 9.2% compared to RT (Figure 4).

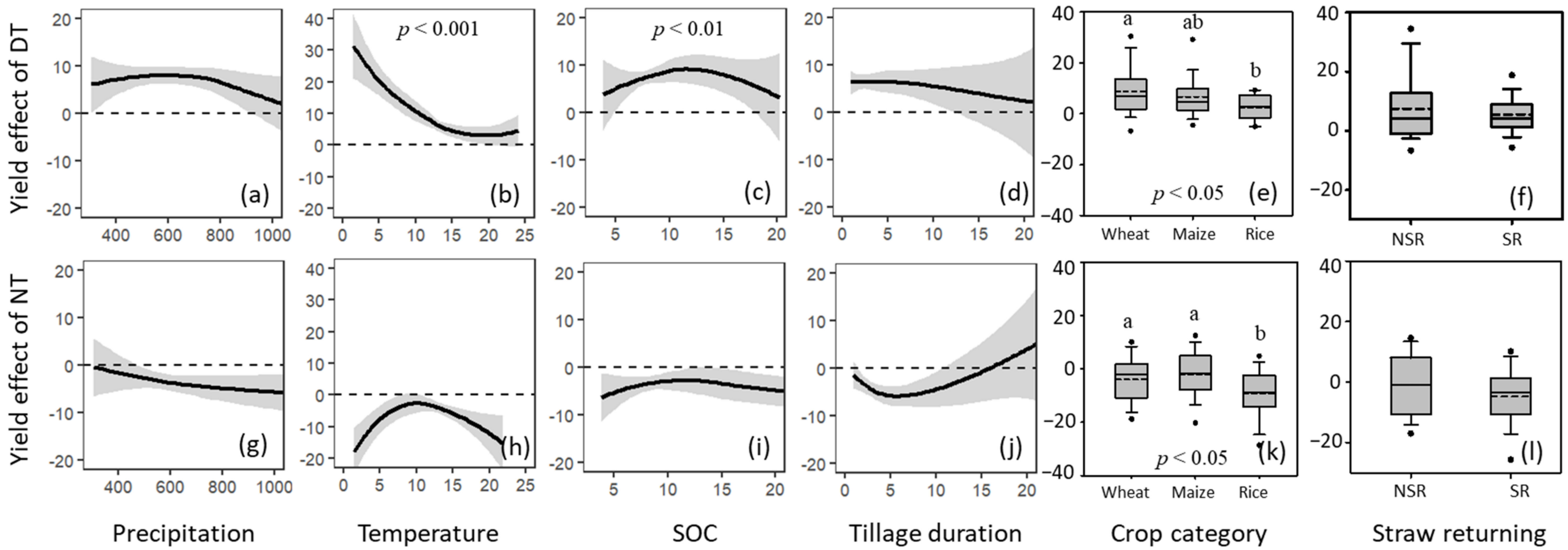

Figure 2. Relative yield percentage changes in DT and NT compared with RT management plans, dependent on climatic conditions ((**a**,**g**), annual mean precipitation; (**b**,**h**), annual average temperature), soil properties ((**c**,**i**), soil organic carbon (SOC)) and experimental conditions ((**d**,**j**), tillage duration; (**e**,**k**), crop category; (**f**,**l**), SR). (**a**–**f**) are for DT practice; (**g**–**l**) are for NT practice. Shaded bands indicate 95% confidence intervals. $p < 0.001$, 0.01, 0.05 indicate significant correlation between tillage-induced yield effects. Different letters for crop category (**e**,**k**) indicate significant difference between treatments at $p < 0.05$. SR, straw returning; NSR, no straw returning; DT, deep tillage; NT, no tillage; RT, rotary tillage.

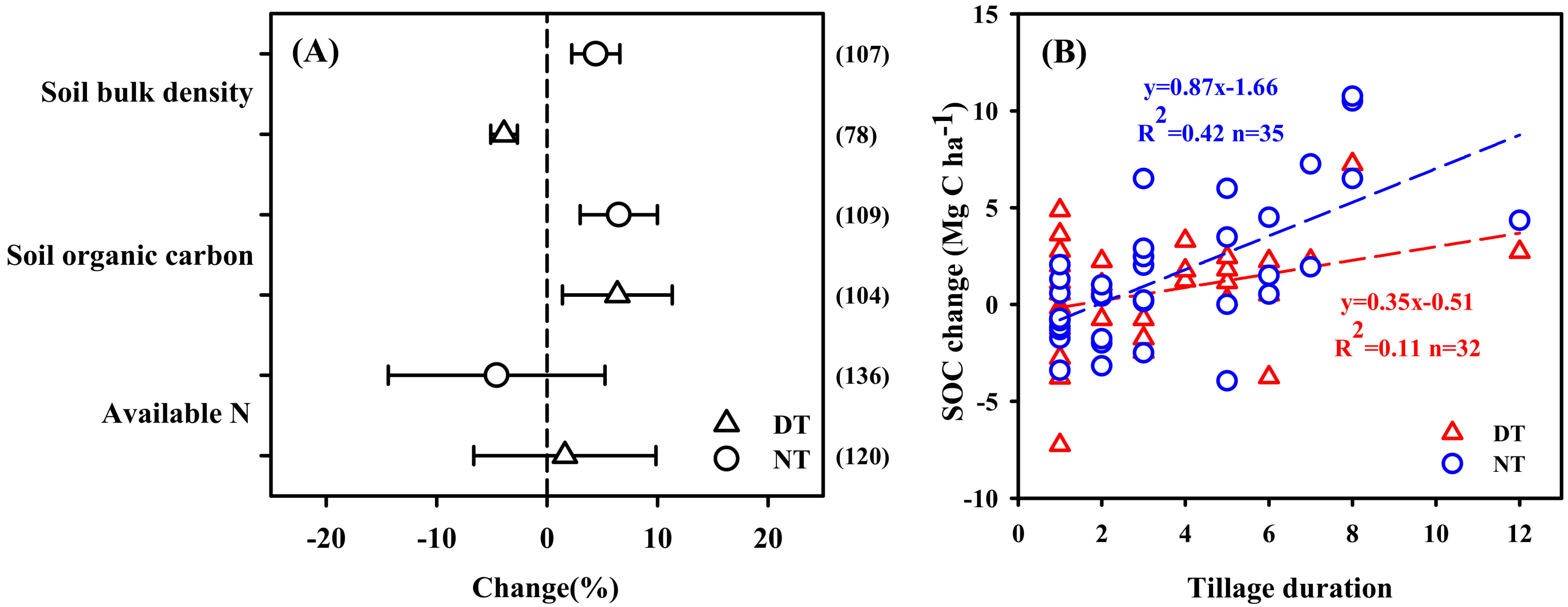

Figure 3. (**A**) Changes in soil properties under different tillage systems. Error bars represent 95% CIs. Triangles and circles indicate the effect size of DT and NT, respectively. The number of observations in each category is shown in parentheses. Differences are considered significant when the CIs do not include zero. (**B**) Linear relationships between tillage duration and SOC changes (Mg C ha^{-1}) under the DT and NT compared with RT management. Tillage duration was plotted against SOC changes for DT (triangles in red) and NT (circles in blue) in comparison with RT management. Red and blue dotted lines are the linear response for DT and NT, respectively. SOC, soil organic carbon; DT, deep tillage; NT, no tillage; RT, rotary tillage.

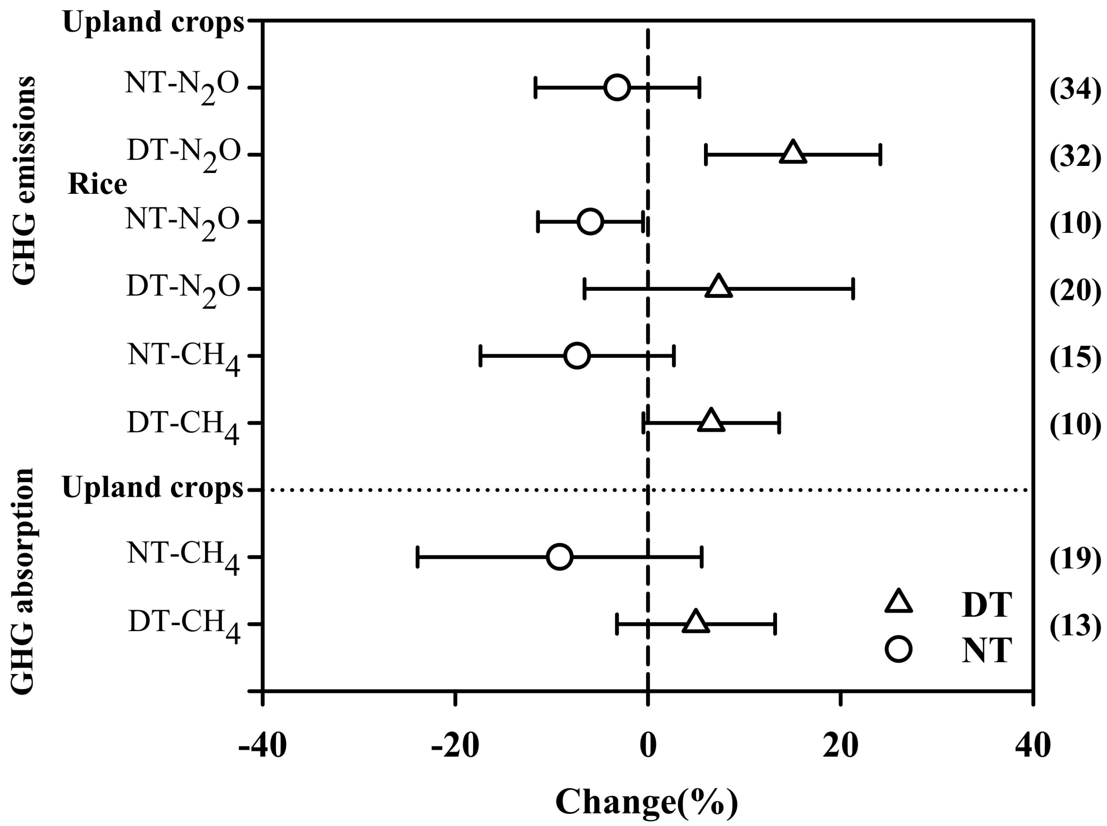

Figure 4. Changes in GHG emissions and absorption for different cropping systems under DT and NT compared with RT management plans. Triangles and circles indicate DT and NT, respectively. The number of observations (n) for each category is shown in parentheses. Error bars represent 95% CIs. Differences are considered significant when the CIs do not include zero. GHG, greenhouse gas; DT, deep tillage; NT, no tillage; RT, rotary tillage.

Overall, DT exhibited field GHG emissions of 167 and 135 kg CO_2-eq ha^{-1} season^{-1} in paddy fields and upland crops, respectively, caused by stimulation of N_2O or CH_4 emissions. NT practice performed better, reducing field GHG emissions by 213 and 99 kg CO_2- eq ha^{-1} in paddy fields and upland crops, respectively (Table 2). Adopting DT management practices led to increased machinery fuel use which increased GHG emissions by 92 kg CO_2-eq ha^{-1}, whereas GHG emissions were reduced by 126 kg CO_2-eq ha^{-1} with NT due to less machinery use relative to RT. Consequently, DT showed total GHG emissions of 259 and 227 kg CO_2-eq ha^{-1} for paddy fields and upland crops, respectively. NT implemented in rice and upland cropping systems reduced the total GHG emissions by 338 and 225 kg CO_2-eq ha^{-1}, respectively, compared with RT (Table 2).

Table 2. Comparison of GHG emissions for different cropping systems under DT and NT compared to RT management plans. Average seasonal emissions of N_2O and CH_4, and the GHG emissions caused by fuel consumption are expressed as CO_2-equivalents. The radiative forcing potentials for N_2O and CH_4 are 298 and 25 times greater, respectively, than for CO_2 in a 100-year time horizon. GHG, greenhouse gas; DT, deep tillage; NT, no tillage; RT, rotary tillage.

Crop	Tillage	GHG (kg ha^{-1})		$GHG_{emission}$ (kg CO_2-eq ha^{-1})		$GHG_{tillage}$ (kg CO_2-eq ha^{-1})	$\triangle$GHG (kg CO_2-eq ha^{-1})
		N_2O	CH_4	N_2O	CH_4		
Upland crops	DT	0.46	−0.09	137	−2	92	227
	NT	−0.34	0.14	−102	3	−126	−225
Rice	DT	0.04	6.19	12	155	92	259
	NT	−0.03	−8.14	−9	−204	−126	−338

3.3. Economic Benefits of Tillage

We calculated the net benefits of the different tillage management systems based on the yield profit, tillage cost, and global warming cost. DT significantly enhanced yield profits, with increases of 1263, 1346, and 1036 CNY ha^{-1} for maize, wheat, and rice, respectively. The reductions in crop yield following NT resulted in profit penalties of 238, 710, and 1918 CNY ha^{-1} for maize, wheat, and rice, respectively. Compared with RT, DT increased labor and machinery costs by 188 CNY ha^{-1}, while NT reduced labor and machinery costs by 407 CNY ha^{-1} (Table 3). Compared with RT, the estimated global warming cost increased by 38 and 44 CNY ha^{-1} under DT; however, these were reduced by 38 and 57 CNY ha^{-1} under NT for upland crops and rice, respectively (Table 3). The results show that DT yielded increased net profit for wheat compared to maize and rice (1120 vs. 1037 and 804 CNY ha^{-1}, respectively). NT showed a total net profit of 207 CNY ha^{-1} for maize, but due to massive yield reductions, rice and wheat showed negative net profits of 1454 and 265 CNY ha^{-1}, respectively (Table 3).

Table 3. Comparison of economic benefits for different cropping systems under DT and NT compared to RT management plans. The relative yield and tillage costs correspond to the yield and tillage costs of DT and NT compared to RT. CNY, Chinese yuan; DT, deep tillage; NT, no tillage; RT, rotary tillage.

Tillage	Relative Yield (kg ha^{-1})			Yield Profit (CNY ha^{-1})			Relative Tillage Costs (CNY ha^{-1})	Global Warming Costs (CNY ha^{-1})			Net Profit (CNY ha^{-1})		
	Maize	Wheat	Rice	Maize	Wheat	Rice		Maize	Wheat	Rice	Maize	Wheat	Rice
DT	574	561	370	1263	1346	1036	188	38	38	44	1037	1120	804
NT	−108	−296	−685	−238	−710	−1918	−407	−38	−38	−57	207	−265	−1454

Note: 1. Maize, wheat, and rice prices were 2.2, 2.4, and 2.8 CNY kg^{-1}, respectively. 2. According to the published literature, the market price of CO_2 closed at 169.36 CNY per ton in 2008.

4. Discussion

4.1. Crop Production

Generally, DT increased crop yield and NT decreased crop yield (Figure 1), consistent with previous comprehensive analyses [5,8,51]. We determined that spike or cob number was the key factor affecting yield as a result of the different tillage practices, and this could be explained by the fact that soil compaction affected spike or cob number and the emergence rate [52]. In terms of agronomic traits, LAI differed significantly, and this was also reported previously, where higher root penetration was associated with increased uptake of soil water and nutrients under DT, resulting in the promotion of leaf growth and dry matter accumulation [15,53].

Our analysis indicated that the yield effect of DT was not sensitive to changes in precipitation, consistent with a previous comprehensive analysis of the Loess Plateau in China [54]. Although intensive soil disturbance may increase soil water evaporation, DT practice could improve the soil structure, porosity, and water-holding capacity, and these inconsistencies may have led to the yield being insensitive to increases in precipitation [16,54]. There was a marked positive yield effect at relatively low temperatures under DT. It is possible that DT loosens soil and warms the arable land, both of which are beneficial to crop yields, especially during low temperatures [21,27]. DT-induced crop yield tended to be higher with an optimal SOC content, as was reported previously [8], and this may be attributed to the increased SOC, which would reduce the effects of soil-water storage and nutrient release. The increased yield response for DT remained stable regardless of the tillage duration, indicating that DT has continuous effects on yield increase [55].

NT reduced crop production relative to RT, consistent with previous results [26,56]. Our study showed that the trend of low yields under NT could be mitigated by certain environmental and management variables. Yield decreased continuously with increasing precipitation, indicating that NT resulted in less yield reduction in arid areas and that excessive precipitation dramatically reduced yield production [54]. Another previous analysis reported that NT performed better under dry conditions, regardless of whether crops were rain fed or irrigated [6]. The yield reduction induced by NT was mitigated by moderate temperatures, suggesting that the implementation of NT in warm regions may increase yield. Continuous NT exhibited a more substantial yield effect, which was consistent with previous reports that a longer NT duration maintained increased yields [6,8]. We noticed a slight reduction in maize yield under NT management, but recent research conducted in the North China Plain showed that the NT effect on maize yield was not significant compared with RT [26].

4.2. Climate Change Mitigation

Higher N_2O emissions were detected in upland crops following DT practice, consistent with previous findings [17,57,58]. Yan et al. (2016) reported that annual N_2O emissions were significantly higher under DT management than under RT and NT, and there was no significant difference between RT and NT [17]. This may be explained by the fact that DT enhances soil microbial activity and accelerates denitrification, thus increasing N_2O emissions [17,21]. NT reduced N_2O and CH_4 emissions in paddy fields compared with cultivated soil, as reported in previous studies [59–61]. The reduced CH_4 emission in paddy fields following NT practice was attributed to the higher soil bulk density and lower dissolved organic carbon content than in cultivated soil [62]. A long-term research project showed that NT could somewhat reduce the emission flux of N_2O compared to RT [59], but the response to the different tillage plans varied according to the environment and management practices [63,64].

Over a whole life-cycle assessment, DT exhibited a positive net total GHG emission in terms of field emissions and energy costs, while NT tended to reduce the total GHG emissions. DT practice simultaneously increased fuel consumption and field GHG emissions [10,57,58]. Rice production in conjunction with DT practices exhibited higher GHG emissions than upland crops, mainly due to the greatly increased CH_4 emissions in paddy fields [34,65]. However, NT resulted in reduced GHG emissions in the soil. This was due to the reduced fuel consumption for NT, and Lu et al. (2017) considered that fuel-usage for tillage was the major producer of GHG emissions [10]. Reduced N_2O or CH_4 emissions were an important component of the total reduction in GHG emissions, and this was especially the case in paddy fields under NT management, where there was a substantial reduction in CH_4 emissions compared with RT and DT [59,60,62].

Tillage management strongly alters the soil structure and SOC distribution and causes changes in the characteristics of the soil properties and soil carbon storage [11,12]. In our study, SOC sequestration increased significantly following the implementation of DT and NT. Additionally, as NT results in less disturbance of the soil structure and a reduction in the decomposition rate of SOC within the aggregates, it has great potential to sequester carbon in the soil and has been widely adopted in croplands for carbon sequestration [56,66]. DT exhibited higher SOC than RT, and this may be ascribed to the mixing and burial of residues at the bottom of the plow [16,56]. In addition, significant differences were recorded under the different tillage management plans for soil bulk density (Figure 3A). NT reduced soil disturbance, and thus the bulk density and penetration resistance were higher than under the other tillage practices [18,67,68]. Meanwhile, DT management by breaking the plow pans, decreased the soil bulk density and enhanced the availability of soil nutrients, all of which were beneficial to root growth and increased tiller numbers (Figure 3A) [14,26,69].

4.3. Economic Benefits

Trade-off relationships between yield profit and relative tillage costs were determined in a comparison of economic benefit, following the implementation of DT and NT. Although the costs increased for DT, they were completely offset by the significant promotion of yield profit for different crop categories [38]. By contrast, NT reduced the costs, which partly offset the reduction in yield profit [10,34]. It is worth noting that a positive net profit of 207 CNY ha^{-1} was determined for maize. This is possibly because NT had only a minor effect on yield, mainly because DT was often implemented in the preceding crop in the North China Plain. DT effectively loosened the soil, and in combination with other management strategies (e.g., SR), these were all beneficial to the yield production [26].

4.4. Limitations and Implications

Our analysis summarized and analyzed the benefits and trade-offs of tillage management plans based on currently available field data; however, there are some limitations. First, the available data on gas emissions (N_2O and CH_4) used in this study are substantially less than those for the crop yield (153 vs. 551 for gas emission and yield), and the database is still not sufficiently large to accurately evaluate gas emissions for DT and NT, especially for rice cropping systems (Figure 4). In the future, more controlled field experiments are needed that can fully examine tillage-induced GHG emissions in different agro-ecological regions to assess the effects of GHG emission more accurately. Second, parameters concerning the effects of management costs and global warming costs induced by the different tillage practices are limited and vary greatly, which may lead to bias in the economic and environmental evaluations. Therefore, future research should consider an expanded investigation of the economic and environmental parameters under diverse cropping conditions. Third, we only calculated GHG emissions and fuel consumption in the equation for the global warming costs and did not consider SOC sequestration since we did not have robust or accurate economic parameters for SOC change. Lastly, different crop rotation patterns or other factors may have potential impacts on the tillage management. For example, Cui et al. (2021) found that under the no tillage practice, the net photosynthetic rate of wheat-maize intercropping was more than 30% higher than that of wheat-maize rotation and rape-maize rotation, thereby affecting the crop yield [70]. Although these limitations may affect the ultimate results, the trends observed for the different tillage systems remain unchanged. We aimed to help those interested in improving the analysis parameters, and the overall results will be beneficial to our understanding of tillage systems in the context of crop production and climate change.

From a sustainability perspective, the choice of tillage management system depends on the agronomic, economic, and environmental benefits, which are largely affected by the tillage-induced crop yield, tillage costs, and GHG emissions. NT has been adopted and has spread throughout the agro-ecological area in China, and in 2014 accounted for 7.3 M ha [71]. Our results have shown that NT has great potential in terms of SOC sequestration and GHG mitigation. Although NT exhibited a significant total yield reduction, the yield penalty can be reduced or even reversed by favorable ambient conditions and agricultural strategies. Our study indicated that the ultimate goals of higher yields and reduced GHG emissions are achievable if guidance and innovative technologies can be adopted by agricultural producers. Through the continued use of NT, agricultural producers will focus increasingly on the economic effects, and reduced economic benefits may prevent farmers from implementing NT in practice. Consequently, subsidy policies are needed to effectively resolve the dilemma between the economic benefits and environmental costs by providing compensation.

This study showed the positive effects of DT practices on crop production, especially when optimal management practices are adopted collectively. However, DT increased GHG emissions, which would hamper the wide-spread use of this technique, especially in today's climate of sustainable agricultural development. Whether this undesirable side-effect of DT practice can be attenuated remains to be fully investigated. In general, the trade-offs and benefits of the tillage management plans investigated in this study may underlie policy formulation, such as the National Planning of Conservation Tillage Project of China and could help policymakers to improve policies for sustainable crop production further while providing an insight into sustainable tillage strategies.

5. Conclusions

Sustainable intensification of agriculture requires a healthy, cultivated soil environment as a prerequisite. Tillage is a soil management strategy that profoundly affects the crop yield, SOC sequestration, and GHG emissions by changing soil properties. Our meta-analysis provides an insight into the trade-offs and benefits of tillage management plans and shows that tillage has a dual influence on crop productivity and climate change mitigation. In general, DT significantly increased crop yield by 7.5%, with higher economic benefits for different crops, but also exhibited higher total GHG emissions. Although NT significantly reduced crop yield by 3.7% and showed negative net economic benefits (except for maize), the total GHG emissions were relatively low. Our study showed that DT management plans should attenuate the environmental costs through abatement strategies to achieve both economic and environmental benefits. NT showed tremendous potential for SOC sequestration and GHG mitigation, and the yield penalty could be reduced by combining optimal management plans to achieve the goal of sustainable development. Clearly, in the future, more attention should be focused on strengthening field management plans to achieve the optimal strategy for tillage practice.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/agronomy11081495/s1. Database resource information: Detailed database resource from previous literature for this meta-analysis, which contained 144 published studies.

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