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RESEARCH ARTICLE

No-tillage effects on grain yield, N use efficiency, and nutrient runoff losses in paddy fields

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Abstract The effect of no-tillage (NT) on rice yield and nitrogen (N) behavior often varies considerably from individual studies. A meta-analysis was performed to assess quantitatively the effect of NT on rice yield and N uptake by rice, N use efficiency (NUE, i.e., fertilizer N recovery efficiency), and nutrient runoff losses. We obtained data from 74 rice-field experiments reported during the last three decades (1983–2013). Results showed the NT system brought a reduction of 3.8 % in the rice yield compared with conventional tillage (CT). Soil pH of 6.5–7.5 was favorable for the improvement of rice yield with the NT system, while a significant negative NT effect on rice yield was observed in sandy soils ($p < 0.05$). N rate, ranging from 120 to 180 kg N ha^{-1}, for at least 3 years was necessary for NT to enable rice yield comparable with that of CT. Furthermore, the observations indicated NT reduced N uptake and NUE of the rice by 5.4 and 16.9 %, while increased the N and P exports via runoff by 15.4 and 40.1 % compared with CT, respectively. Seedling cast transplantation, N rate within the range 120–180 kg N ha^{-1}, and employing NT for longer than 3 years should be encouraged to compromise between productivity and environmental effects of NT implementation in rice fields.

Keywords No-tillage · Rice yield · Nitrogen uptake · Nitrogen use efficiency · Nutrient runoff loss

Highlights 1. The meta-analysis shows NT reduced rice grain yield compared with CT.
2. NT could lead to higher nutrient runoff losses from fields compared with CT.
3. Combining NT and management techniques enables yield and NUE comparable with CT.

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Introduction

No-tillage (NT) farming is a method of growing crops without disturbing the soil by tillage. Since 1970, NT has been predominant in a number of countries because of the energy crisis, but it has been employed mostly on dry agricultural land for crops such as wheat, maize, cotton, and others. In recent years, a number of countries (e.g., Japan, India, Malaysia, Indonesia, and China) have promoted the implementation of NT in rice paddy fields (Díaz-Zorita et al. 2002; Soane et al. 2012; Zhang et al. 2011).

Paddy rice fields provide one of the main staple foods for more than half of the global population, utilizing only 11 % of the cultivated land (Wang et al. 2015). In Asia and some other developing regions, most rice fields have been cultivated by conventional tillage (CT), with relatively few implementing NT until several decades ago. However, the development of agricultural machinery, the increases in labor and energy costs, and the prominence of environmental issues in recent years, have encouraged increasing numbers of rice farmers and regional managers to choose NT as an alternative cultivation method. NT is presumed to reduce economic input and obtain significant eco-efficiency from rice production systems (Jat et al. 2014; Xu et al. 2015). However, the effects of NT on the rice yield and the behavior of the nutrients are still relatively unknown.

Yield is an important indicator to evaluate an agricultural management practice; however, the effect of NT on the rice yield varies considerably in relation to the spatial location. For instance, in eastern China, NT significantly increased the rice yield compared with CT because of the improvement in the physical and chemical properties of the soil (Gao et al. 2004). In the northwestern Himalayan region, NT did not have a significant effect on the rice yield as the system brought about higher organic carbon content and lower bulk density, compared with CT (Panday et al. 2008). These findings indicated the varying effects of NT on the rice yield.

The variables associated with the effects of NT on the rice yield mainly pertain to soil properties (e.g., texture and pH) and field management practices (e.g., N fertilizer application rate, rice planting method, crop rotation, residue retention, and the duration of the NT implementation) (Gathala et al. 2011; Huang et al. 2012b; Mambani et al. 1990). Comprehensive meta-analysis has been conducted by Lundy et al. (2015) and Pittelkow et al. (Pittelkow et al. 2015a b) recently to evaluate the influence of various crops and environmental variables on the NT yields and showed the decline in yield following the conversion from tillage to NT, including for rice, but they only scooped yield data from English written literatures. Moreover, in these papers, the most important variables were aridity, NT duration, crop rotation, residue, N rate, and irrigation. Considering rice fields are often in flooded state, we take no account of the variables of aridity and irrigation, but other important variables like soil pH, texture, and planting method were included in this study.

The yield response to NT farming derives from the NT effect on the N uptake by the rice plant (Xu et al. 2010). We hypothesized that NT simultaneously influenced the amount of N uptake by the plant and the N use efficiency (NUE, i.e., fertilizer N recovery efficiency). In addition, agricultural systems often have to find a balance between crop yield and nutrient-associated environmental issues, such as N and P exports from the cultivated fields (Chen et al. 2014). Thus, the effects of NT on the NUE and the nutrient exports via runoff, relevant to the different variables, were considered in this meta-analysis.

In this meta-analysis study, we have used data from 74 rice-field experiments reported during the last three decades (1983–2013) to gain an insight into the factors that contribute to the high rice yield and improved nutrient uptake associated with NT.

Material and methods

Data collection

The data selection process was done by using specific keywords (no-till, zero-till, direct drilling, rice yield, N uptake, N use efficiency, and N/P loss) in an internet search of Web of Science, Google Scholar, and China Knowledge Network, for the period 1983 to 2013. Only studies that conformed to specific requirements were selected. The requirements were (1) the data were obtained from field experiments (pot experiments were excluded); (2) data on side-by-side comparisons of NT and CT were reported, but the data reported did not include data on minimum tillage; (3) the total N treatment rate was the same for NT and CT; (4) the treatments were duplicate at least; (5) the data were considered only once if the same data were repeated in different studies; (6) the total P and K rates applied to the rice field were equal; and (7) at least ten observations of the side-by-side comparisons of the rice yield, N uptake, NUE, and N or P exports via runoff were needed because a small sample size, i.e., database, would lead to bias in the results of the analysis. Table 1 shows the 74 studies that conformed to our standards.

The categories of the variables were selected according to soil pH, soil texture, planting method, rotation, residue, N rate, and the duration of NT. Soil pH was divided into three classes, namely, ≤6.5, 6.5–7.5, and ≥7.5. Soil texture was grouped into two categories, namely, sandy (a combination of sandy loam, sand, and sandy clay loam) and non-sandy (a combination of silt loam, clay, silty clay loam, and clay and loam). The planting method was classified into three categories, namely, direct seeding, transplanting, and cast transplanting. The N rate was categorized into <120, 120–180, or >180 kg N ha^{-1}, and the duration of the NT system by <3 and ≥3 years. In addition, the analysis also considered whether rotation (yes/no) and residue retention (yes/no) were applied. No residue retention meant residue was completely taken away from the field.

Data analysis

All comparisons between CT and NT pertaining to rice yield, N uptake, NUE, and N or P loss were included for each study to separate data points ("observations"). We used the natural log (LnR) of the response ratio as our effect size (Hedges et al. 1999; Linquist et al. 2013). The studies were weighted by replication, and the mean effect sizes were estimated with the weight:

$$\ln\mathrm{R} = \ln\left(\frac{X\mathrm{e}}{X\mathrm{c}}\right) \tag{1}$$

$$w\mathrm{i} = n \tag{2}$$

$$\overline{\ln\mathrm{R}} = \frac{\sum (\ln \mathrm{Ri} \times w\mathrm{i})}{\sum w\mathrm{i}} \tag{3}$$

where X_e and X_c are the mean values of the rice yield, N uptake, NUE, and N and P exports via the runoff for the CT and NT treatments, respectively. W_i is the weight for the *i*th observation, and *n* is the number of field replications. lnR is the effect size of the rice yield, N uptake, NUE, and N and P exports via runoff from the *i*th observation.

Table 1 Summary of studies included in our meta-analysis indicating study reference, country, total N, and soil pH of the research site

Study reference	Country	Total N	Soil pH
Chauhan and Opeña (2012)	Philippines	180	6.5
Chen (2007)	China	195	6.59
Chen et al.(2007)	China	107	5.34
Cheng et al.(2008)	China	150	6.04
Cho et al.(2001)	Korea	0	5.1
Dai (2009)	China	150	5.15
Dong (2009)	China	150	6.32
Du et al.(2013)	China	240	6.82–6.87
Feng et al.(2004a)	China	150	5.61–5.78
Feng et al.(2004b)	China	0	5.61–5.78
Feng et al.(2006a)	China	150	6.31
Feng et al.(2006b)	China	150	6.31
Gao et al. (2004)	China	125.6	7.1
Gathala et al. (2011)	India	172.5	8.1
Guo et al.(2007)	China	177	6.24
Han et al.(2009)	China	0	5.57
Huang et al.(1990)	China	–	–
Huang et al.(1999)	China	–	–
Huang et al.(2005)	China	225	6.4
Huang et al.(2010)	China	90	–
Huang et al.(2011)	China	150	6.04
Huang et al.(2012c)	China	150	6.04
Huang et al. (2012a)	China	185	6.45
Huang et al. (2012b)	China	195	6.46
Iijima et al.(2005)	Japan	133	–
Jat et al.(2009)	India	150	8.2
Jiang et al.(2007)	China	145.5	5.36
Jiang and Xie (2009)	China	124.2	6.65–6.8
Jiang et al.(2009)	China	–	–
Kushwaha et al.(2005)	India	80	–
Li et al.(2001)	China	157.5	5.77
Li et al.(2006)	China	193	–
Li et al.(2010)	China	0	6.58
Lin (2014)	China	210	–
Liu et al.(2006)	China	225	–
Liu et al.(2009)	China	225	–
Mahata et al.(1990)	India	60	5.2–5.8
Mambani et al.(1989)	Philippines	75	6.6
Mambani et al. (1990)	Philippines	75	6.6
Mishra and Singh (2007)	India	120	–
Mishra and Saha (2008)	India	80	5.1
Mishra and Singh (2012)	India	120	7.3
Nascente et al.(2013)	Brazil	110	6.4
Ogunremi et al.(1986a)	Nigeria	120	–
Ogunremi et al.(1986b)	Nigeria	–	–
Olofintoye (1989)	Nigeria	100	5.3
Panday et al. (2008)	India	100	6.4
Parihar (2004)	India	–	–
Pearce et al.(1999)	USA	–	–
Pittelkow et al.(2012)	USA	168	5
Qin et al.(2006)	China	127.5	–
Qin et al.(2010)	China	225	5.2
Rodriguez and Lal (1985)	Nigeria	0–150	5.9
Saharawat et al. (2010)	India	160	7.8
Saito et al.(2010)	Benin	48	–
Tang (2006)	China	195	6.15
Tang et al.(2011)	China	180	–
Tian et al.(2013)	China	150	
Tripathi et al.(2007)	India	150	–
Tsuji et al.(2006)	Japan	55	–
Wang et al.(2001)	China	–	–
Wang et al.(2010)	China	180	–
Wu et al.(2013)	China	280	6.18
Xu et al. (2010)	China	0	5.78
Yan et al.(2005)	China	–	7.6
Yang (2011)	China	0	6.58
Yang et al.(2013)	China	225	6.33
Zeng (2011)	China	151.8	7.57
Zhang et al.(2010)	China	240	6.3
Zhang et al. (2011)	China	0	5.39–5.85
Zheng (2012)	China	225	6.33
Zhu et al.(1999)	China	165	5.3
Zhu et al.(2006)	China	150	7.8
Zhuang et al.(1999)	China	–	–

We used the random effect model of the Metawin 2.1 software to generate the mean effect and 95 % bootstrapped confidence intervals (CIs, 4999 iterations). The effects were considered significant if the 95 % CI did not overlap with zero, while they were considered not significant if the 95 % CI did overlap with zero (Curtis and Wang 1998; Morgan et al. 2003). To estimate the NT effect, the results for the analyses on lnR were back-transformed and reported as the percentage change from the conventional tillage (control), as [R-1] × 100 % (Ainsworth et al. 2002). The p values for the differences between the categories of the studies were calculated by the resampling techniques incorporated in the Metawin 2.1 software (Linquist et al. 2013).

Results

NT effect on rice yield

The practice of NT has led to an overall decline of 3.83 % (95 % CI = −4.38~−3.28 %) in the rice yields (Fig. 1). NT had no significant effect on the rice yield of acidic soils (soil

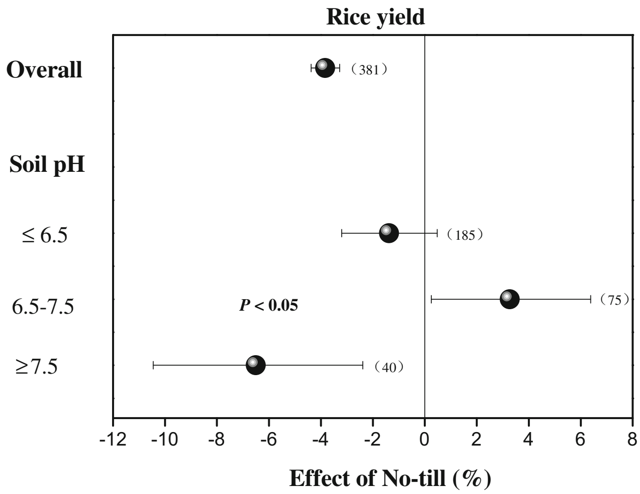


Fig. 1 The overall benefit of no-tillage (NT) on rice yield and the influence of soil pH (≤6.5, 6.5–7.5, ≥7.5) on rice yield under NT

pH ≤ 6.5). However, a significant positive effect ($p < 0.05$) was indicated for neutral soils (pH 6.5–7.5), and the yield increased by 3.27 % (95 % CI = 0.25~6.38 %) compared with that of CT. However, in alkaline soils (pH ≥ 7.5), the NT system resulted in a remarkable decline of 6.51 % (95 % CI = −10.45~−2.39 %) in the rice yield in comparison with that of the CT system (Fig. 1).

NT was more able to maintain the rice yield in non-sandy paddy soils than in sandy soils. In sandy paddy soils, the NT system brought about a 10.23 % (95 % CI = −13.03~−7.35 %) reduction in the rice yield, while in non-sandy soils, NT increased the rice yield, but not significantly compared with CT (Fig. 2).

Seedling transplanting, especially cast transplanting, could diminish the negative effect of NT on the rice yield; however, with direct seeding, NT brought about a significant decline of 6.05 % (95 % CI = −8.28~−3.76 %) in the rice yield, compared with that of CT (Fig. 2).

Although the differences in the effect of NT on rice yield with either crop rotation or residue retention were not significant, NT brought about a 2.0 % reduction (95 % CI = −3.95~−0.09 %) without implementing rotation, and 2.91 % (95 % CI = −4.66~−1.13 %) ($p < 0.05$, Fig. 3) without implementing residue retention.

There was a significant difference in the NT effect on the rice yield among different N rates. Compared with CT, the NT system reduced the rice yield by 10.46 % (95 % CI = −11.87~−9.03 %) when the total applied N rate was less than 120 kg N ha^{-1}. The negative effect gradually decreased with the increase of the N rate, and there was no significant difference when the N rate reached 120–180 kg N ha^{-1}. When the N application rate exceeded this figure, a significant decline in the rice yield was shown, with a decrease value of 4.38 % (95 % CI = −5.20~−3.55 %) ($p < 0.05$, Fig. 4).

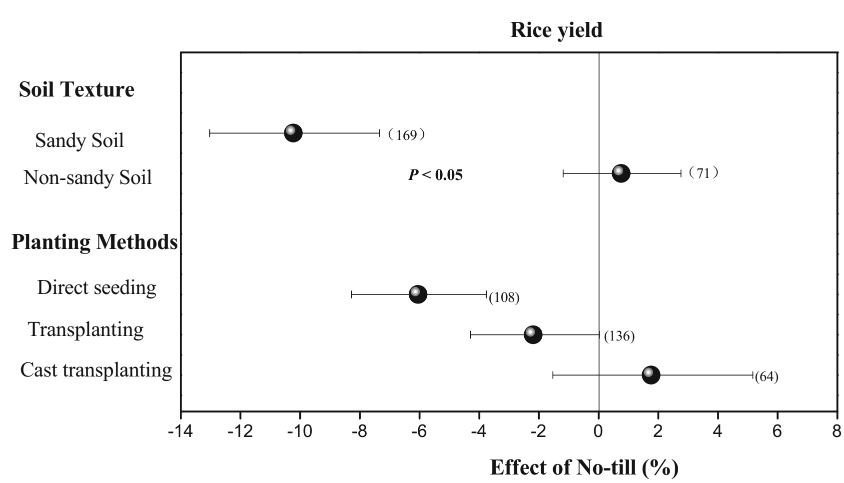
As indicated in Fig. 4, the success of NT, in comparison with CT, in achieving a higher rice yield is dependent on the system being employed for at least 3 years. Rice yield declined by 4.10 % (95 % CI = −5.68~−2.44 %) for NT implemented for less than 3 years but did not decrease any more when the practice lasted longer than 3 years.

NT effect on N uptake and N use efficiency

On average, NT decreased the N uptake of the rice plant by 5.44 % (95 % CI = −2.44~−8.35 %) and NUE by 16.94 % (95 % CI = −26.89~−5.64 %), when each one was used separately, compared with the CT system (Fig. 5). Without residue retention, in particular, the corresponding decreases in the values of N uptake and NUE were 6.29 % (95 % CI = −9.69~−2.75 %) and 18.41 % (95 % CI = −31.27~−3.15 %) (Fig. 5), respectively. However, combining the NT system with residue retention could show N uptake and NUE values comparable with those of the CT system.

In addition, with direct seeding, a significant difference was found in the N uptake and the NUE between NT and CT, with NT bringing about a reduction of 9.63 % (95 % CI = −14.5~−5.5 %) in the N uptake and 14.97 % (95 %

Fig. 2 The influence of soil texture (sandy soil (sandy loam, sand, sandy clay loam) and non-sandy soil (silt loam, clay, silty clay loam, and clay and loam)) and planting methods (dry seeding, transplanting, and cast transplanting) on rice yield under NT



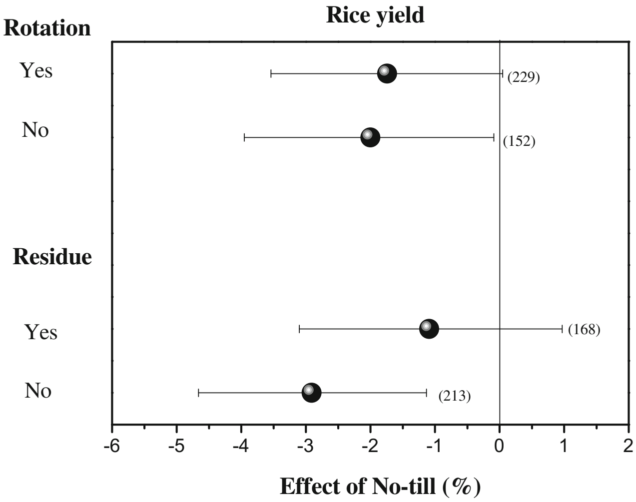


Fig. 3 The influence of residue (yes and no) and rotation (yes and no) on rice yield under NT

CI = −29.93~−0.97 %) in the NUE. Conversely, with transplanting, no significant difference was observed for either variable relevant to the CT or the NT systems (Fig. 5).

NT effect on nutrient runoff losses

On average, NT increased the N and P exports via runoff by 15.45 % (95 % CI = 13.2~17.75 %) and 40.06 % (95 % CI = 36.81~43.39 %) compared with CT (Fig. 6). Furthermore, in the absence of crop rotation or residue retention, the N and P exports via runoff for NT were much higher than were those for CT. Especially in the absence of crop residues, the N and P exports via runoff were significantly increased by 73.69 % (95 % CI = 32.5~124.2 %) and 99.14 % (95 % CI = 71.29~131.52 %). The corresponding increases of the values relevant to the absence of crop rotation

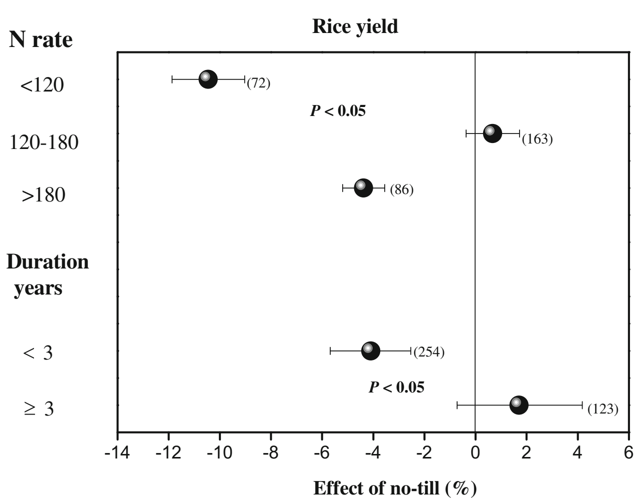


Fig. 4 The influence of total N rate (< 120, 120–180, >180 kg ha^{-1}) and duration years (<3, ≥3 years) on rice yield under NT

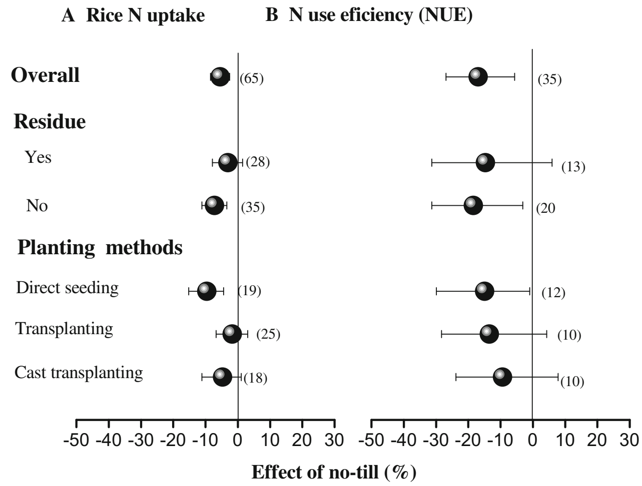


Fig. 5 The overall benefit of no-tillage (NT) on rice N uptake and N use efficiency (NUE) and the influence of residue (whether applied or not) and planting methods (dry seeding, transplanting, and cast transplanting) on rice N uptake and NUE under NT

were 63.9 % (95 % CI = 40.0~83.52 %) and 83.87 % (95 % CI = 60.82~110.92 %), respectively.

Discussion

Although an overall negative impact from NT was observed in this analysis and in others (Lundy et al. 2015; Pittelkow et al. 2015a, b), the system was deemed successful at maintaining a comparable or higher rice yield under certain conditions. These conditions are (1) in neutral soils (pH 6.5–7.5), NT brings about a higher rice yield in comparison with that of CT ($p < 0.05$), possibly because in such soil, N losses (especially for ammonia volatilization) from the paddy fields will not appear significantly (Vymazal et al. 1998). Moreover, neutral to slightly alkaline soils favor nitrification rate (Norton

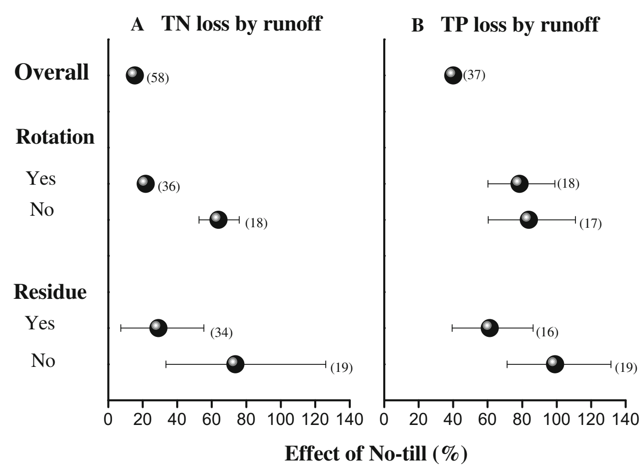


Fig. 6 The overall benefit of no-tillage (NT) on paddy field runoff loss of total N load (TN) and the influence of rotation (whether applied or not) and residue (whether applied or not) on the benefit of paddy field runoff loss of total N load (TN) under NT

2008). However, excessively high pH of the soil increases the risk of NH_3 volatilization (Francis et al. 2008), which cannot ensure sufficient nutrient available for rice growth under NT. (2) In non-sandy soils, NT has a comparable rice yield compared with that of CT. The effect of NT in non-sandy soils is much more beneficial than the significant negative effect of the system in sandy soils. This phenomenon is ascribed mainly to the low hydraulic conductivity of most non-sandy rice soils and the increased leaching of N in the highly permeable rice soils (Liang et al. 2014a). Conversely, the findings from rainfed dryland crops, such as maize, indicate that the beneficial effect of NT on the crop yield in sandy soils could probably be attributed to the improved well-drained hydraulic conditions and the greater conservation of soil moisture (Rusinamhodzi et al. 2011). (3) Seedling transplanting (especially cast transplanting) diminishes the negative effect of NT on the rice yield, i.e., from negative with direct seeding to comparable with the transplant method because better anchorage following transplanting could contribute to increase in yield under NT. The transplanting method helps the rice seedlings to obtain sufficient nutrition from the NT implemented soils (Gao et al. 2004). However, other researchers have pointed out that NT coupled with direct seeding could result in water and labor savings for the rice cultivation systems (Bhushan et al. 2007; Saharawat et al. 2010). (4) Crop rotation and residue retention improve the negative effect of NT on the rice yield. Both rotation and residue retention are conducive to increasing the soil properties, fertility, and the microbial activities that facilitate the relationship of nutrient requirement and demand between the soil and the plant (Huang et al. 2012a). (5) At an N rate of 120–180 kg N ha^{-1}, the rice yield increases with an increase of the N rate. However, when an optimum level of N input is reached, the extra N fails to increase the rice yield. Although this yield response to the N rate is applicable to both NT and CT, the effect size could be larger for the latter (CT). (6) NT has to be employed for longer than 3 years. This condition is supported by various studies, which indicated that employing NT for a period shorter than 3 years would not result in improved rice yield compared with that of CT. This finding suggests that the benefits of the NT system, i.e., improvements to the soil properties and the soil biological activity, are not reflected during the initial years after implementing the system (Mishra and Saha 2008; Saharawat et al. 2010).

With regard to the N uptake of rice and NUE, we found that the size of the database of the side-by-side comparisons of NT and CT was much smaller than that pertaining to rice yield. The amount of information on the rice yield was approximately five to ten times larger than that of the N uptake and NUE. In an effort to reduce the computational and/or analytical bias in this study, the small database only included side-by-side comparison in N uptake with specific variable-related observations >10. Only two variables, namely, residue and planting method, conformed to this requirement (Fig. 5). Although database sizes were different, similar results were observed for NT effects on rice production system as follows: (1) overall, NT decreased the N uptake and NUE; (2) some variables, such as crop residue retention and transplanting of seedlings, improved the negative effect of NT on all of the abovementioned statistics. These results suggest that appropriate agricultural management practices could help to increase the N uptake and NUE of the NT system by promoting N fertilizer utilization. In this study, we observed negative NT effects on either the N uptake of the rice or the NUE, mainly because NT was not implemented for an appropriate length of time.

As environmental implication concerned, NT generally reduces soil erosion and nutrient export from most non-irrigated lands due to an associated increase in surface residue and reduction in surface runoff (Fu et al. 2006; Brouder and Gomez-Macpherson 2014); however, our meta-analysis indicated that this does not apply to flooded rice fields. NT induced significantly higher N and P exports via runoff from the rice fields compared with CT, irrespective of rotation or residue retention being employed (Fig. 6). This could be attributed to the NT system enriching the surface soil with more nutrients due to less nutrient uptake by rice plant (Brouder and Gomez-Macpherson 2014), while leading to a greater potential for leaching (Zhu et al. 2012). Another reason for higher N and P losses could be the water management practice. Mid-season drainage is a popular water management practice in our dataset. This practice allows the field to drain during the middle of the growing season before flowering stage of rice. During the drain, N and P losses could be enhanced. A combination of NT with either crop rotation or residue retention helped to reduce the negative effects of NT on the N and P exports via the runoff from the rice fields (Fig. 6). Specifically, a significant difference was found in the effect of NT on the export of N when crop rotation was employed or not employed. Residue retention did not increase the N and P exports associated with the NT system, compared with the CT system.

In addition, we also found that NT brought about a larger effect size on the increase of the P exports via the runoff (mean size: 40.06 %) than on the N exports (mean size: 15.45 %), compared with the CT system (Fig. 6). This is probably attributable to the various pathways leading to N loss, such as ammonia volatilization, denitrification, and N leaching, while the main pathway leading to P loss was by surface runoff and/or drainage (Liang et al. 2013, 2014a, b).

One important issue worthy to point out is that although the vast majority of the papers used in this meta-analysis were from non-English journals, the dataset on nutrient cycling and NT is still limited in size. Thus, our dataset may be skewed to favor Chinese cropping management and soil types. In order to get more convincing conclusion, more references should be included from other regions of the world and increase the size of the dataset.

Conclusions

This meta-analysis indicated that NT brought about a decline in the rice yield, N uptake, and NUE and increased the potential losses of N and P via runoff, compared with the CT system. Our analysis only suggested rotation can be the optimal management practice to increase yield and NUE, while minimize exports in NT rice system. However, residue management should also be encouraged in rice NT system because retaining residue did not increase N, P loss, especially when the decomposition of residues can release large amounts of nutrients. In addition, residue management may have other important functions like inhibiting weeds' growth and replacing part of fertilizer input into the rice fields. NT, rotation, and residue have been considered as three "pillars" in conservational agriculture (CA). In future studies, we can focus on clarifying the differences of nutrient cycling or transformation and field eco-efficiency in different CA-managed rice fields. A life-cycle analysis would be necessary to evaluate completely the effect of NT on productivity and the environment during both the rice and the rotation crop seasons.

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