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Reduction in nitrogen fertilizer use results in increased rice yields and improved environmental protection

Huaiyu Wang[a*], Ruifa Hu[a], Xiaoxue Chen[a], Xuhua Zhong[b], Zuting Zheng[a], Nongrong Huang[b] and Chunling Xue[c]

[a]School of Management and Economics, Beijing Institute of Technology, Beijing, People's Republic of China; [b]Rice Research Institute, Guangdong Academy of Agricultural Science, Guangzhou, People's Republic of China; [c]College of Economics and Management, South China Agricultural University, Guangzhou, People's Republic of China

ABSTRACT

Overuse of nitrogen fertilizer represents a considerable environmental problem globally, but especially in China. Recently, a recent approach on an experimental scale based on the diffusion of the so-called Three-Control Technology (TCT) successfully alleviated the overuse of nitrogen fertilizer in southern China villages in the Guangdong Province, serving as a reference point for other rice-producing countries tackling similar challenges. Here, we assessed the correlation between rice yields and reduction in the use of nitrogen fertilizer following the introduction of TCT. Our study was based on the collection of primary data from 248 households randomly selected from four rice-growing areas of Guangdong Province, China. Our results show that TCT significantly improved the efficiency in the use of nitrogen. Crucially, participating farmers, including both full adopters and partial adopters, were found to fundamentally change their application practices of nitrogen fertilizer, resulting in major improvements in the local soil and water systems.

KEYWORDS

Rice production; Three-Control Technology (TCT); nitrogen fertilizer; nitrogen fertilizer retrusion; environmental impact

Introduction

Global overuse of nitrogen fertilizer is a key contributor to climate change as well as to soil and water pollution (Gruber & Galloway, 2008; Gu, Ju, Chang, Ge, & Vitousek, 2015; Guo et al., 2010; Huang & Yang, 2017; IPCC, 2007). China is the world's largest consumer of nitrogen fertilizer, accounting for over 30% of world nitrogen consumption, one-fifth of which is used for rice production (Heffer, 2008; Peng et al., 2010). Rice is the main staple food in Asia, therefore striking a balance between maintaining food security and addressing the most urgent environmental challenges remains a challenge for many developing nations in the region. Appropriate action is needed to improve the productivity and protect the environment in the context of sustainable agricultural production (Chen et al., 2014; Chhay et al., 2017; FAO, 2011). Knowledge-based N management practice can be considered an effective way to improve the agricultural sustainability and ensure food security while increasing economic return (Majeed et al., 2017; Xia et al., 2017).

On average, Chinese rice farmers overuse nitrogen fertilizer by 30–80%, resulting in considerable environmental problems not only for the areas that overuse nitrogen fertilizer but also for downstream regions due to the connected nature of the rice paddy systems (Heffer, 2008; Ju, Kou, Zhang, & Christiel, 2006; Norse, 2005; Peng et al., 2010). In some Chinese provinces, the average rate of nitrogen (N) application is as high as 300 kg per hectare (Hu et al., 2007; Peng et al., 2002), with a global average of less than 100 kg per hectare for rice (FAO, 2006). A survey in Guangdong Province found that the average rate of nitrogen fertilizer application rate exceeds 220 kg per hectare in some counties (Hu

CONTACT Ruifa Hu ruifa@bit.edu.cn
*Present address: Sustainable Development Research Institute for Economy and Society of Beijing, Beijing, People's Republic of China
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et al., 2007; Zhong, Huang, & Zheng, 2007). As a result, plants only utilize a fraction of the supplied nitrogen fertilizer, commonly around 20–30%, and a large proportion of N is thus accumulating in the surrounding environment, with the anticipated consequences for the environment (Peng et al., 2006). Improving the efficiency of nitrogen fertilizer by reducing nitrogen fertilizer input in rice production has thus been of considerable interest to scientists and policy makers both in China and elsewhere in the region.

The use of chemical fertilizer at unsuitable times of the growing season has resulted in an excessive accumulation of nitrogen fertilizer on Chinese farms (Huang, Hu, Cao, & Rozelle, 2008). Earlier research suggested that China's rice farmers apply most of the nitrogen fertilizer during the early stages of rice growth. More specifically, in most regions of China, more than 90% of the total nitrogen fertilizer used is applied within the first 10 days after transplanting (Hu et al., 2007). In Guangdong Province, for instance, farmers typically apply nitrogen fertilizer two to three times in the first 15 days after transplanting, resulting in more than 80% of nitrogen fertilizer being used during the basal and tillering stages (Hu et al., 2007). Excessive nitrogen fertilizer application during the early growth stage usually results in long-term nitrogen losses, as a consequence of which nitrogen accumulates in the environment surrounding of the paddy field, as the crop lacks demand for nitrogen during this growth stage due to insufficient development of the root system (Peng et al., 2002). Moreover, this fertilization practice can spur excessive lateral tiller production, leading to the growth of an unhealthy canopy that may actually decrease grain yields by increasing susceptibility to dislodging and damage from pests and diseases (Peng et al., 2002, 2006; Zhong, Huang, & Zheng, 2007). To avoid this, rice farmers employ mid-season drainage to regulate population size and achieve a healthy canopy, with mixed results (Peng et al., 2002).

The traditional practice of applying fertilizer during the early growth stage and mid-season drainage commonly results in low nitrogen fertilizer efficiency and unhealthy canopy development. As a consequence, farmers must apply even more nitrogen fertilizer into their rice paddies. To reduce the amount of nitrogen fertilizer, it is important to improve the efficiency of applying nitrogen fertilizer. Recently, several strategies have been developed to improve the efficiency of nitrogen fertilizer application, such as site-specific nutrition management technology and best management practices, which have been extended in various countries including Bangladesh, China, Philippines, Vietnam, Thailand, and India (Alam, Karim, & Ladha, 2013; Dobermann et al., 2002; Huang, Huang, Jia, Hu, & Xiang, 2015; Ju et al., 2006; Peng et al., 2010; Snyder, Bruulsema, Jensen, & Fixen, 2009). Empirical studies indicate that these strategies improve the efficiency of nitrogen use in chemical fertilizer, and ultimately, increase farmers' incomes (Huang et al., 2008; Yamano, Arouna, Labarta, & huelgas, 2016). However, while most of these technologies have yet to be widely adopted in China, the Three-Control Technology (TCT) is now widely accepted and has been extensively adopted in China's Guangdong Province since its introduction in 2007.

TCT is a nutrient management technology for rice production and promotes the nutrient uptake of rice plants through the postponing of fertilizer application, namely from the early growth stage to the middle and late growth stages, a strategy called 'nitrogen fertilizer retrusion'. This approach results in a delay in fertilizer application, and change in the distribution of fertilizer amount, resulting in improved efficiency of nitrogen uptake by the plant. The core change to fertilizing practices, in addition to a 10–30% reduction in nitrogen fertilizer input, is that TCT postpones the fertilizing time from the early growth stage to the middle and late growth stages. This assumes that nitrogen fertilizer is applied in the following manner: 40% as basal, 20% at mid-tillering, 30% at panicle initiation, and 10% at heading (Zhong et al., 2010).

TCT was developed by the Rice Research Institute of Guangdong Academy of Agricultural Science (GDRRI) (Guangdong, China) and the International Rice Research Institute (IRRI) (Manila, Philippines). It was shown on an experiment scale that the application of TCT reduces nitrogen fertilizer input through changing fertilizer practices (controlling nitrogen fertilizer) and also reduces the rice lodging rate due to lowering the number of unproductive tillers (controlling unproductive tillers). Furthermore, it allows the reduction in pesticide use as the quality of the rice population and the canopy is improved (controlling pests) (Zhong, Huang, & Zheng, 2007; Zhong, Huang, Zheng, Peng, & Buresh, 2007; Zhong et al., 2010).

Earlier establishment of demonstration models allowed for an effective information campaign across Guangdong province (Zhu, 2000). Thus, TCT became widely accepted across the main rice-farming regions in China, particularly in Guangdong province.

With the endorsement by the government, new as well as improved agricultural technologies such as TCT were introduced to farmers through the national and provincial agricultural extension system. This system is commonly divided into four stages, namely programme design including land parcel chosen and village and farmer selection, technology demonstration and monitoring, feedback and large-scale extension. Following the development of a new technology, the government initiates on-farm demonstrations. Based on the cultivated land selected, farmers are chosen randomly as demonstration farmers to apply the new technology in their fields. By increasing the number of demonstration farmers in villages, information about the new technology spreads and encourages other farmers to adopt the technology as well. The key component for the diffusion of agricultural technology through the extension system is that continuous plots should be chosen, not farmers. Therefore, to properly estimate the effects of agricultural technology adoption, such procedure meets the requirement that farmers should be chosen randomly. Accordingly, when TCT was officially released in January 2007, the provincial government initiated an on-farm demonstration and extension programme by randomly selecting rice farmers in the main rice-growing area in Guangdong Province. By 2012, nearly all the rice-growing counties in the province had introduced and conducted TCT demonstrations.

The positive effects of TCT on the increase of rice yields and reduction of nitrogen fertilizer application are well-documented (Zhong et al., 2010). In those earlier experimental studies, a reduction of 20% in nitrogen input was achieved. In addition, unproductive tillers and lodging of the rice crop were reduced through avoiding excess N uptake and mid-season drainage. Also, the amount of fungicides and insecticides used was reduced as a result of which better ventilation condition was achieved, and a healthier rice canopy was observed (Zhong et al., 2010). Although this technology was shown to be effective under experimental conditions, few field surveys have assessed the degree at which farmers have adopted TCT for large-scale production, as well as the effects TCT adoption has on rice yield and environmental protection.

For example, during preliminary studies, we observed that not all farmers strictly followed the guidelines provided for the use of TCT. On the contrary, adoption of TCT by farmers varied widely in terms of the timing of fertilizer application, and the variety and amount of fertilizers used for rice production. Such variation may affect the real impact of TCT, necessitating an in-depth evaluation of the effects of technology adoption and assessment of the gap between TCT use under controlled conditions, and its actual effects on farms. This study aims to address this knowledge gap by answering two research questions. First, does the use of TCT improve the efficiency of nitrogen application in rice cultivation, thus assisting farmers to reduce nitrogen fertilizer usage and increase yields? Second, does the application of TCT reduce rice lodging and pest infestation followed by the improvement of the cultivation environment for rice.

Materials and methods

Data

All farmers were informed in advance by the enumerators concerning the purpose and content of the questionnaire, with written consent obtained prior to interviewing. Enumerators were trained and dispatched into the field to interview the farmers and fill in the household questionnaire. In addition, local farmers agreed with the research objectives of this study and gave permission for the recording of all input–output information. Farmers unwilling to be interviewed could withdraw from the study at any time. Furthermore, participants were notified that all information would be de-identified to ensure anonymity.

The data used in this study were obtained through a random survey in Guangdong Province in 2012. To ensure that farmers are chosen randomly during the extension programme, a parcel of paddy land was chosen for the demonstration programme, rather than the household itself, thus avoiding the selection of rich farmers or farmers with a good relationship with the village head or government official. As a result, the samples were randomly selected and investigated sites are shown in Figure 1. Two rice crops are grown within a year in the survey areas and this is called double rice cropping system. The first rice crop being grown in March and early April and harvested in July and August is called early rice, while the second rice crop being grown in July and harvested in October and November is called late rice.

Four sample counties (Gaoyou, Lianjiang, Renhua, and Xinhui) were randomly selected from the four rice-producing areas in the province (i.e. north,

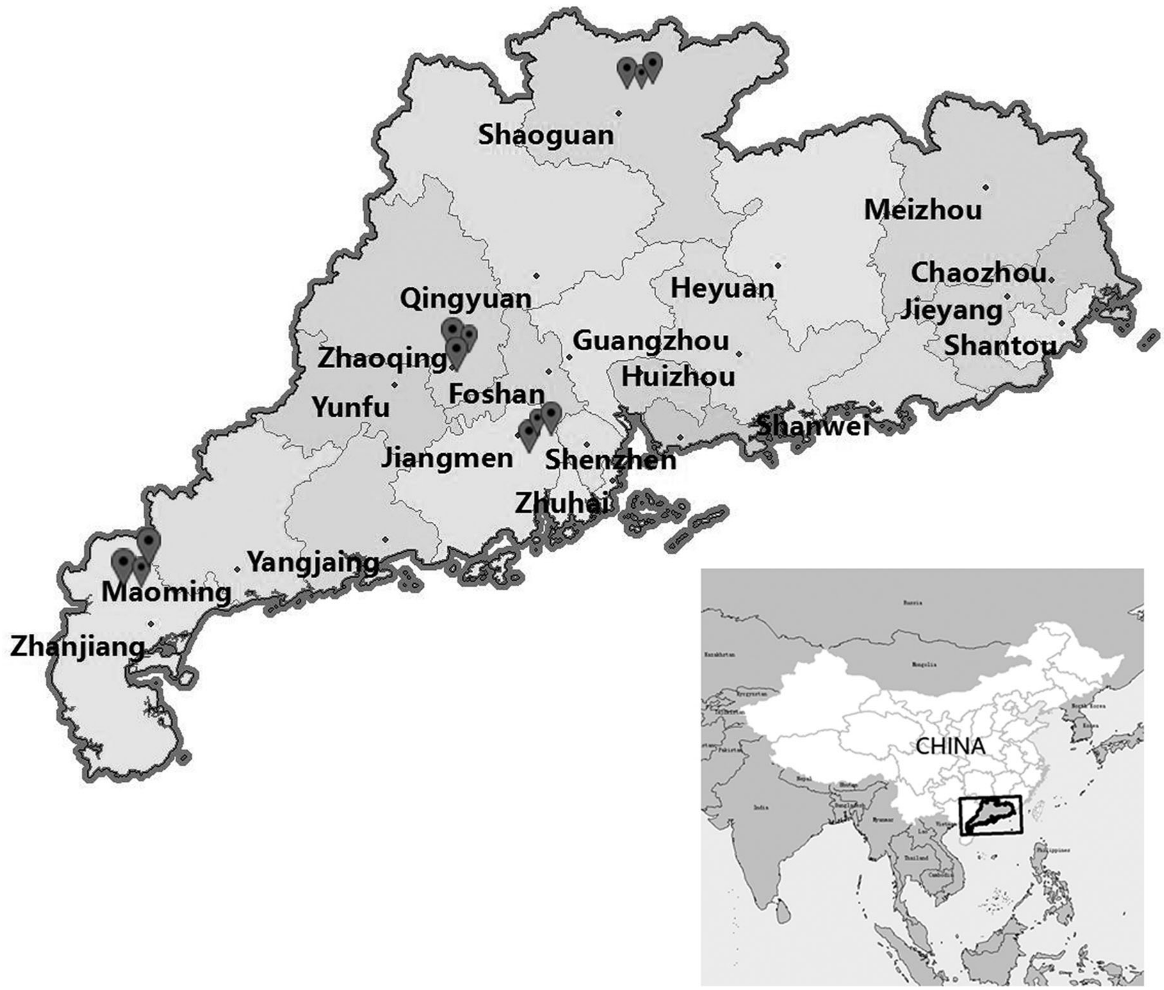

Figure 1. Investigated sites in Guangdong province, China.

central north, central south, and southwest). In each sample county, three villages were randomly selected from the village list and designated either as demonstration, adjacent, or control villages. Villages chosen as demonstration villages were required to have had exposure and access to the information and support related to TCT provided by their respective local governments. Villages were selected to represent the current status of the farmers, acting as the variable used to assess the effect of this technology extension. Categorization of rice farmers as adopters or non-adopters was used as an indicator to help estimate the impact of technology adoption in farming practice. One demonstration village was first randomly selected from a list of villages with demonstration programme for TCT provided by the local agricultural government, with adjacent and control villages subsequently selected from the same list. The adjacent and control villages were approximately 3–5 km and over 20 km away from the demonstration village, respectively. In the control villages, no extension activity or TCT services was available, and farmers had limited access to technology information due to the distance to demonstration villages. In each village, 18–22 farm households were randomly selected for interviews, with a total of 248 rice farmers from 12 villages in the 4 counties. Among these farmers, 74 farm households were selected from demonstration villages and 92 and 82 farm households from adjacent and control villages, respectively. The enumerators, using producer-recall interviewing techniques, collected information on inputs and outputs at the plot level, including detailed information on fertilizer use and rice varieties. Only the

Table 1. Sample structure and TCT adoption among different types of villages in 2012.

	Full adopters	Partial adopters	Non-adopters	Total
Early rice season				
Demonstration villages	24	22	28	74
Adjacent villages	42	24	26	92
Control villages	4	2	75[a]	81
Total	70	48	129	247
Late rice season				
Demonstration villages	21	30	23	74
Adjacent villages	37	30	25	92
Control villages	3	1	78	82
Total	61	61	126	248

[a]There was one household in this group that did not grow early rice in 2012.

household's largest plot in each season was included in our investigation. In total, the survey obtained information on 247 early rice plots and 248 late rice plots, as shown in Table 1.

In addition, adoption rates for TCT varied across sample villages, as each village contained a mix of farmers with or without experience in adopting TCT (Table 1). We defined farmers who declared that they had not made any changes in their farmer fertilizer practices (FFP) in the past 10 years as *non-adopters*, and those who had adopted TCT as *adopters*. However, among the farmers who claimed to have adopted TCT, we identified farmers who lacked any experience with TCT. To distinguish these farmers, we defined the farmers who followed the TCT instructions (i.e. postponed their first fertilization until approximately 10 days after transplanting and reduced the amount of nitrogen fertilizer used) as *full adopters*. Those who had changed their FFP in the past 10 years and partially adopted TCT practices in terms of the timing and amount of nitrogen fertilizer used were defined as *partial adopters*. In total, only four households existed in the control villages that adopted TCT to some extent, which indicates that the samples in the control villages were not contaminated. The breakdown of the three types of sample farmers across the three types of villages is shown in Table 1.

Methods

A number of factors may affect the impact of TCT adoption on nitrogen fertilizer usage and rice yields, as measured in this study. In order to control these factors, we used multiple regression analysis. To determine the net impact of TCT adoption, the following models were used:

$$\begin{aligned} \mathrm{NF} = {} & \propto_N + a_N{*}\mathrm{Adopter} \\ & + b_N{*}\mathrm{demonstration}{*}\mathrm{Adopter} \\ & + c_N{*}\mathrm{NF\ price} + h_N{*}\mathrm{Characteristics} + \varepsilon_N, \end{aligned} \quad (1)$$

$$\begin{aligned} \mathrm{Lodging\ rate} = {} & \propto_L + a_L{*}\mathrm{Adopter} \\ & + b_L{*}\mathrm{demonstration}{*}\mathrm{Adopter} \\ & + d_L{*}\mathrm{Drying\ land} + e_L{*}\mathrm{NF} \\ & + g_L{*}\mathrm{Inputs} + h_L{*}\mathrm{Characteristics} + \varepsilon_L, \end{aligned} \quad (2)$$

$$\begin{aligned} \mathrm{Yield} = {} & \propto_Y + a_Y{*}\mathrm{Adopter} \\ & + b_Y{*}\mathrm{demonstration}{*}\mathrm{Adopter} \\ & + e_Y{*}\mathrm{NF} + f_Y{*}\mathrm{Lodging\ rate} + g_L{*}\mathrm{Inputs} \\ & + h_Y{*}\mathrm{Characteristics} + \varepsilon_Y. \end{aligned} \quad (3)$$

NF refers to the amount of nitrogen fertilizer being used in the plot (in kg/ha). Lodging rate refers to the share of lodging area in total rice area in 2012. Yield refers to the rice yield in the investigated paddy (in t/ha).

Adoption is indicated via three dummy adoption variables. Taking *non-adopter* as the base category, two dummies, *full adopter* (1 if yes; 0 if no) and *partial adopter* (1 if yes; 0 if no), were generated. Farmers in demonstration villages may have improved access to extension services, perhaps facilitating their adoption of the technology. Therefore, interaction variables – the demonstration village dummy interacted with the three adoption variables (*full adopter*, *partial adopter*, and *non-adopter*) – were used to measure the effects of living in a demonstration village.

The *nitrogen fertilizer price (i.e. NFprice)*, as included in Equation (1), measures the unit value price of nitrogen fertilizer paid by a farmer in Yuan per kilogram. This variable is used to control for how the nitrogen fertilizer price impacts farmers' decisions regarding the amount of nitrogen fertilizer to use. As farmers normally use mid-season drainage (i.e. drying land) to limit rice lodging during harvest, *drying land* is included in Equation (2) as a control variable (1 if yes; 0 if no). Several input variables, such as the amounts of *nitrogen fertilizer*, P_2O_5, and K_2O fertilizers used (in kg/ha), *labour input* (hours/ha), and *frequency of pesticide application* (number of times), were included in Equations (2) and (3).

In order to keep both demographic and farming characteristics constant, the three regression models included variables for rice variety, farmer and farm characteristics, natural disaster impacts, and region. The *rice variety* grown on the investigated plot was specified in terms of grain quality (1 if high quality; 0 if not) and whether a hybrid rice variety was grown (1 if yes; 0 if no). *Farmer and farm characteristics* included the age (in years) and education (in years attained) of the household head, whether he or she was a village leader (1 if yes; 0 if no), the size of the farm (in hectares), and the number of houses in the compound. Weather effects were accounted for by including a dummy variable for *natural disaster* impacts, which was equal to one if rice in the studied plot was affected by either drought or flood during the studied season. *County* dummy variables were included to account for any county-specific effects.

The models are specified as follows:

$$\begin{aligned} \mathrm{NF} = {} & \propto_N + a_N \mathrm{Adopter} + b_N * \mathrm{demonstration} * \mathrm{Adopter} \\ & + c_N * \mathrm{NFprice} + h_{N1} * \mathrm{grain\_quality} \\ & + h_{N2} * \mathrm{hybrid} + h_{N3} * \mathrm{Disaster} + h_{N4} * \mathrm{Age} \\ & + h_{N5} * \mathrm{Edu} + h_{N6} * \mathrm{leader} + h_{N7} * \mathrm{farmsize} \\ & + h_{N8} * \mathrm{houses} + \varepsilon_N, \end{aligned} \tag{4}$$

$$\begin{aligned} \text{Lodging rate} = {} & \propto_L + a_L * \mathrm{Adopter} \\ & + b_L * \mathrm{demonstration} * \mathrm{Adopter} \\ & + d_L * \text{Drying land} \\ & + e_L * \mathrm{NF} + g_{L1} * \mathrm{Input\_NF} \\ & + g_{L2} * \mathrm{Input\_}P_2O_5 + g_{L3} * \mathrm{Input\_}K_2O \\ & + g_{L4} * \mathrm{Input\_Labor} + g_{L5} * \mathrm{Input\_other} \\ & + h_{L1} * \mathrm{grain\_quality} + h_{L2} * \mathrm{hybrid} \\ & + h_{L3} * \mathrm{Disaster} + h_{L4} * \mathrm{Age} + h_{L5} * \mathrm{Edu} \\ & + h_{L6} * \mathrm{leader} + h_{L7} * \mathrm{farmsize} \\ & + h_{L8} * \mathrm{houses} + \varepsilon_L, \end{aligned} \tag{5}$$

$$\begin{aligned} \mathrm{Yield} = {} & \propto_Y + a_Y * \mathrm{Adopter} \\ & + b_Y * \mathrm{demonstration} * \mathrm{Adopter} + e_Y * \mathrm{NF} \\ & + f_Y * \text{Lodging rate} + g_L * \mathrm{Inputs} \\ & + h_{Y1} * \mathrm{grain\_quality} + h_{Y2} * \mathrm{hybrid} \\ & + h_{Y3} * \mathrm{Disaster} + h_{Y4} * \mathrm{Age} \\ & + h_{Y5} * \mathrm{Edu} + h_{Y6} * \mathrm{leader} + h_{Y7} * \mathrm{farmsize} \\ & + h_{Y8} * \mathrm{houses} + \varepsilon_Y. \end{aligned} \tag{6}$$

The nitrogen fertilizer and yield models (Equations (1) and (3)) were estimated using the ordinary least squares (OLS) regression, and the lodging rate model (Equation (2)) was estimated via the Tobit method. All variables were specified in log terms except for the lodging rate and various dummy variables.

Results and discussion: TCT adoption and impacts

Farmers' TCT adoption

Table 1 depicts the process of the TCT diffusion (Table 1). Of the 248 farm households, 118 early and 122 late rice farmers reported that they had adopted TCT in 2012. This represents nearly half of the rice farmers in the sample villages. Of those farmers in demonstration villages, 46 farmers growing early rice (62.2%) and 51 farmers growing late rice (68.9%) declared that they had adopted TCT. In the adjacent villages, the numbers were 66 (71.7%) and 67 (72.8%) for early and late rice farmers, respectively. The situation was different in the control villages: of the 82 sampled farmers, only 6 early rice farmers (7.4%) and 4 late rice farmers (4.9%) reported that they had adopted the technology. These results indicate that China's agricultural demonstration system has facilitated access to agricultural technologies for a large number of farmers, particularly those in villages adjacent to demonstration villages.

Among farmers who reported adopting the technology, only 59.3% early rice farmers and 50% late rice farmers were full adopters, i.e. both the timing and amount of nitrogen fertilizer application followed the instructions (Table 1). Of those farmers residing in demonstration villages, 47.8% early rice farmers and 58.8% late rice farmers had not fully adopted the technology. In adjacent villages, the numbers of TCT partial adopters were 36.4% and 44.8% for early and late rice farmers, respectively. Among the adopters in the control villages, 33.3% early rice farmers (two rice farmers) and 25% late rice farmer (one rice farmer) lacked any evidence for full adoption of TCT. These results indicate that fully adopting the TCT guidelines remains a considerable logistical challenge for rice farmers to change their traditional practices. Farmers' traditional practices have been implemented for decades and it used to be successful to help rice farmers improve the rice yields. Local rice farmers believe that a strong root would be necessary to maintain the yield while the base fertilizer is very important to help the plant to develop its root. As mentioned earlier, the core change to fertilizing practices, in addition to a certain amount of reduction in nitrogen fertilizer input, is that TCT postpones the fertilizing time from the early growth stage to the middle and late growth stages. This is very different from farmers' traditional practices and knowledge on the fertilizer application. Many rice farmers doubted whether TCT adoption could be successful and they will add some urea if the plants are not as big as the ones they used to have. Scientists have to explain the theoretical background to rice farmers which is very helpful for farmers to understand and exactly follow the instructions. Otherwise, farmers' improper fertilizer application, either the amount or the timing of application, may lead to an unsuccessful adoption. This would give a bad example for other rice farmers. Thus, consequently and continuous training and technical support are both necessary during the rice seasons to monitor and answer farmers' questions.

Analysis of our survey data showed that only about half of all farmers adopted the technology following TCT guidelines. Even in demonstration and adjacent villages, only two-thirds of rice farmers showed signs of using the technology. Among TCT adopters, only about half had fully adopted the technology. The other half adjusted the timing of nitrogen fertilizer application, as recommended, but did not reduce the amount of fertilizer. Despite this semi-adoption, the rice yields increased, possibly encouraging farmers to fully adopt TCT. Furthermore, some farmers applied more nitrogen fertilizer than prior to adoption, or even more than non-adopters, possibly because they tend to increase the amount of fertilizer usage at the first time as they worry about the potential yield since the rice plants looked not as strong as those treated by the traditional fertilizer application.

Three indicators were used to assess the impact of TCT on the reduction of nitrogen fertilizer, increase of rice yields, and susceptibility to dislodging. Nitrogen fertilizer input and rice yields were used to measure the effect of TCT on nitrogen fertilizer efficiency (controlling nitrogen fertilizer). The lodging rate, defined as the share of rice area with lodge in total rice area of the plot investigated, was used to test whether the technology could improve the quality of the rice population and canopy (controlling unproductive tillers) and reduce the occurrence of pests (controlling diseases and insects).

The analyses of our survey show that the application of TCT significantly decreased the use of nitrogen fertilizer by rice farmers. On average, compared to *non-adopters* (who applied 206 kg/ha (early rice) and 213 kg/ha (late rice)), *full adopters* applied 45 kg/ha (early rice) and 58 kg/ha (late rice) less nitrogen fertilizer and partial adopters applied 20 kg/ha (early rice) and 20 kg/ha (late rice) less nitrogen fertilizer (Table 2, row 1). Both *full* and *partial adopters* thus applied less nitrogen fertilizer than the *non-adopters*, reducing their fertilizer expenditures (Table 2, row 4). Although the frequency of fertilization was more for *full* and *partial adopters* than for *non-adopters*, the difference was only 0.22 times less (Table 2, row 5).

Table 2. Nitrogen fertilizer input, lodging rate, yield, and other indices of rice production among *full adopters*, *partial adopters*, and *non-adopters* of TCT in 2012.

	Early rice				Late rice			
	Full adopters	Partial adopters	Non-adopters	ANOVA	Full adopters	Partial adopters	Non-adopters	ANOVA
Nitrogen fertilizer input (kg/ha)	161 (46.0)	186 (62.8)	206 (90.3)	***	155 (48.6)	183 (59.6)	213 (94.0)	***
P_2O_5-fertilizer input (kg/ha)	58.7 (40.0)	75.1 (46.6)	74.4 (52.9)	*	60.1 (38.9)	66.7 (44.1)	76.39 (56.4)	*
K_2O-fertilizer input (kg/ha)	112 (51.5)	114 (64.1)	117 (92.1)		110 (56.0)	106 (57.7)	123.90 (91.5)	
Fertilizer expenditure (Yuan/ha)	2527.3 (1048.5)	2860.2 (1450.6)	3010.3 (1581.5)	*	2479.4 (1087.7)	2603.3 (1211.6)	3121.8 (1585.0)	***
Fertilizing frequency (times)	3.41 (0.50)	3.44 (0.58)	3.22 (0.62)	**	3.39 (0.53)	3.44 (0.53)	3.29 (0.60)	
Lodging rate during harvest (%)	3.1 (8.3)	3.98 (9.6)	10.60 (22.2)	***	1.10 (4.7)	4.39 (16.0)	6.22 (18.5)	
Pesticide application frequency (times)	3.34 (0.81)	3.23 (0.75)	3.16 (0.66)		3.46 (0.74)	3.44 (1.07)	3.30 (0.78)	
Yield (kg/ha)	7116 (1400)	6317 (1478)	5499 (1467)	***	7039 (1473)	6875 (1463)	5483 (1511)	***
Number of observations	70	48	129		61	61	126	

Note: Numbers in parentheses are standard error values.
***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

These results also demonstrate that the use of TCT improved the traits of the entire rice plant population' and canopy quality and increased yields. Compared to the lodging rates in the harvest season, 10.6% (early rice) and 6.22% (late rice) reported by *non-adopters* (Table 2, row 6), *full adopters* reported rates of only 3.1% (early rice) and 1.1% (late rice) and *partial adopters* reported rates of 3.98% (early rice) and 4.39% (late rice). The average rice yields on farms of *non-adopters* were 5499 kg/ha (early rice) and 5483 kg/ha (late rice). These yields are significantly lower than those obtained by either *full adopters* (7116 kg/ha for early rice and 7039 kg/ha for late rice) or *partial adopters* (6317 kg/ha for early rice and 6875 kg/ha for late rice) (Table 2, row 9).

Effects of TCT adoption on rice production

In order to assess the effects of TCT adoption in farmers' fields on nitrogen fertilizer use, productivity, and rice lodging, we performed multiple regression analysis. As shown in Table 3, our regression analysis yielded insights into the positive effects of TCT adoption in large-scale production. *Full adopters* of TCT significantly reduced the amount of nitrogen fertilizer by 15% and 27% for early and late rice planting, respectively. The lodging rate among *full adopters* was significantly lower (20.39%) than that among *non-adopters* for the early rice crop.[1] Rice yields for the early and late rice crops significantly increased by 11% and 13%, respectively. Together, these results demonstrate that the implementation of TCT has achieved its 'three controls' objective in the farmers' fields. Furthermore, these results 'mirror' outcomes from the initial experimental studies, suggesting that rice yields can be improved in large-scale production while farmers reduce the amount of nitrogen fertilizer. Importantly, the reduction of nitrogen fertilizer contributes to environment sustainability of rice production.

However, no significant differences were found between *partial adopters* and *non-adopters* in terms of nitrogen fertilizer input levels and rice lodging rates both in early rice and in late rice season. As defined earlier, partial adopters are those who changed their fertilization practice in the past 10 years, but partially adopted TCT in terms of the timing and amount of nitrogen fertilizer usage. Although partial adoption contributed little to the reduction of nitrogen fertilizer amount, rice yield produced by partial adopters in late rice season is still increased by 12% (Table 3, row 2, column 6) compared to that of non-adopters. Given that the amount of nitrogen fertilizer used changed relatively little, the observed increase in rice yields might be due to the change of fertilization timing. Both correct timing and suitable amount of fertilization are essential to improve nitrogen fertilizer efficiency in the paddy field which need to be considered to develop and expand the management technology such as fertilization management. The adoption of management technology is different from the varietal adoption. Changing the rice variety requires a complete adoption of new technology. However, agricultural management practice is a complex process that involves more than varietal adoption. Therefore, the term partial adopters is defined in terms of the behaviour, but the calculation of varietal adoption is based on the share of rice area planted with improved variety. The definition and its method indicate that changing farmers' traditional practice maintained for years is challenging.

Our regression results provide strong evidence that rice yields for rice farmers in demonstration villages were higher compared to those in adjacent and control villages. To estimate the effect of demonstration programme in the selected village on adoption of TCT, we introduced the interaction variables of the adoption dummy with the demonstration village dummy in our regression models. In the models for nitrogen fertilizer input and lodging rate, the coefficients of three interaction variables, i.e. *demonstration *full/ *partial/ *non-adopter*, were insignificant (Table 3, columns 1, 2, 4, 5; rows 3–5). However, the coefficients of interaction variables of *demonstration *non-adopter* in the early and late rice models (Table 3, column 3, 6; row 5) and *demonstration *full adopter* in the late rice model (Table 2, column 6; row 5) were significant. Together, these results suggest that exposure to demonstration plots helped farmers to efficiently improve their production technologies and increase their rice yields. The results of the multiple regression estimates using the two-stage least squares method (provided in the supplementary material) were similar to our OLS estimations. Based on such household samples, the results are robust and could provide a reference for other regions where nitrogen fertilizer is applied in excess.

Conclusions

As the main staple food crop, overuse of fertilizer and pesticides now represent the two main environmental

Table 3. Regression results for TCT effects on nitrogen fertilizer input, lodging rate, and yield.

	Early rice			Late rice		
Variable	Nitrogen fertilizer input (kg/ha)	Lodging rate (%)	Yield (kg/ha)	Nitrogen fertilizer input (kg/ha)	Lodging rate (%)	Yield (kg/ha)
TCT adoption dummies (base category = non-adopters)						
Full adopter	−0.15**	−20.39*	0.11***	−0.27***	−16.89	0.13***
	(0.07)	(10.49)	(0.03)	(0.07)	(18.71)	(0.04)
Partial adopter	−0.11	−8.09	0.05	−0.10	−3.16	0.12***
	(0.08)	(10.50)	(0.04)	(0.08)	(17.84)	(0.04)
Interaction terms with demonstration village variable						
Demonstration*full adopter	−0.10	−5.71	0.06	−0.05	−10.40	0.09*
	(0.09)	(14.29)	(0.04)	(0.10)	(28.59)	(0.05)
Demonstration*partial adopter	0.12	−18.70	0.01	0.01	17.05	0.06
	(0.10)	(15.38)	(0.05)	(0.09)	(21.24)	(0.05)
Demonstration*non-adopter	−0.05	2.23	0.06*	−0.10	3.49	0.07*
	(0.07)	(10.54)	(0.03)	(0.09)	(18.91)	(0.04)
Control variables						
Nitrogen fertilizer price (Yuan/kg)	−0.27**			−0.24**		
	(0.11)			(0.12)		
Drying land (drying land = 1)		−36.66***			31.12*	
		(8.20)			(17.86)	
Lodging rate (%)			−0.001**			−0.0003
			(0.001)			(0.0008)
High grain quality (high quality = 1)	−0.05	7.96	0.04	0.13**	8.34	0.001
	(0.05)	(8.19)	(0.02)	(0.06)	(13.58)	(0.03)
Hybrid variety (hybrid = 1)	0.02	0.88	0.18***	0.05	−5.30	0.18***
	(0.05)	(8.02)	(0.03)	(0.07)	(15.88)	(0.03)
Natural disaster (affected = 1)	0.24***	13.71	−0.52***	−0.002	16.73	−0.37***
	(0.09)	(11.78)	(0.04)	(0.07)	(16.08)	(0.04)
Household head age (years)	−0.23*	23.07	−0.03	−0.22*	−4.09	−0.04
	(0.13)	(18.39)	(0.06)	(0.13)	(29.61)	(0.06)
Household head education (years attained)	0.01	2.11	−0.01	0.01	1.98	0.001
	(0.01)	(1.35)	(0.004)	(0.01)	(2.22)	(0.004)
Village leader (leader = 1)	−0.06	12.79*	−0.01	−0.06	−1.70	0.01
	(0.06)	(7.53)	(0.03)	(0.06)	(13.79)	(0.03)
Farm size (ha)	0.04	−4.18	0.01	0.03	−5.53	−0.03*
	(0.03)	(5.09)	(0.01)	(0.03)	(8.77)	(0.02)
Number of houses (number)	0.09	3.55	−0.01	0.10*	25.57*	−0.01
	(0.06)	(8.07)	(0.03)	(0.06)	(13.63)	(0.03)
Nitrogen fertilizer (kg/ha)		10.13	0.01		−5.85	−0.006
		(9.20)	(0.03)		(16.38)	(0.03)
P_2O_5 fertilizer (kg/ha)		0.69	0.01		9.64	−0.01
		(1.55)	(0.004)		(9.26)	(0.004)
K_2O fertilizer (kg/ha)		0.05	0.003		1.31	0.001
		(3.00)	(0.01)		(6.30)	(0.01)
Labour input (hours/ha)		0.03	−0.01		−1.36	−0.02
		(4.68)	(0.01)		(7.74)	(0.02)
Other inputs (Yuan/ha)		0.99	−0.003		−0.21	−0.001
		(0.68)	(0.002)		(0.98)	(0.002)
Frequency of pesticide application (times)		42.08**	0.04		31.76	0.01
		(17.79)	(0.05)		(25.07)	(0.05)
Constant	6.24***	−237.6**	8.62***	6.07***	−154.8	8.92***
	(0.52)	(93.07)	(0.30)	(0.53)	(153.1)	(0.33)
Observations	247	247	247	248	248	248

Note: The numbers in parentheses are standard error values. County dummy variables are included but not reported.
***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

challenges during rice production in China (Peng et al., 2002; Peng, Tang, & Zou, 2009; Zhang, 2007). Excess application of nitrogen fertilizer is partially responsible for the overuse of pesticides and also decreases grain yields by increasing the susceptibility to lodging and damage from pests and disease (Cu, Mew, Cassman, & Teng 1996; Peng et al., 2010; Peng et al., 2009). The improvement of productivity could lead to an improvement in the farmers' livelihoods, eventually acceleration local and regional economic growth to achieve the sustainable development of agriculture in the context of economic development (Ha, Feike, Angenendt, Xiao, & Bahrs, 2015). Our study provides strong evidence that the introduction of TCT in Guangdong Province, China significantly reduces the input of nitrogen fertilizer by farmers, as a consequence of which the yields of both first- and second harvest rice increases. Our analysis indicates that the implementation of TCT can significantly reduce rice lodging rates by decreasing the number of unproductive tillers, thereby reducing nitrogen fertilizer losses and improving nitrogen fertilizer efficiency in farmers' field. Importantly, the use of TCT also significantly improved the rice population and canopy quality, creating a healthy cultivation environment that was more resistant to pests.

Since 2008, the provincial government has recommended the TCT as part of an extension programme for all rice paddy in Guangdong Province. By 2012, nearly all rice-producing counties in the province had access to TCT. In addition, the Chinese Ministry of Agriculture (MOA) endorses TCT within their technology extension programmes and recommends the approach to the national extension system. On the basis of these policies, TCT has been advertised to all rice-growing area in the country. Such outcomes provide instructive examples for farmers currently using excessive amounts of nitrogen fertilizer in China and elsewhere in rice-growing regions. If the area of TCT adoption might be expanded nationwide in subsequent years, it would be a considerable contribution to increase rice yield and alleviate the overuse of nitrogen fertilizer on a large scale and, more importantly, to result in a major improvement for local soil and water systems.

Despite these encouraging future prospects, farmers appear to be hesitant in adopting TCT as their normal modus operandi. This reluctance in converting to knowledge-based agricultural management technologies remains a major challenge for scientists, extension officers and policy makers. More farmers training and technical support as well as extension service would be needed for the proposed agriculture practices (Sanz-Cobena et al., 2017). As a result, additional efforts from governments and researchers are essential for full implementation across agricultural production areas.

Nonpoint source pollution originates from various sources dispersed into the ground or from human activity and has become the most widespread type of pollution (Liu et al., 2013; Lu et al., 2015), and nitrogen fertilizer has been found to be the single greatest contributor to pollution in China (Yang, Zhang, Yang, & Yang, 2009; Zhang, 2005). It is crucial to maintain food security while simultaneously achieving environmental sustainability of rice production. Reducing nitrogen input and improving the efficiency in uptake are two highly effective ways to achieve this goal. TCT is an instructive example for the use of technology in fostering environmental sustainability of food production. Encouraging more farmers to correctly adopt TCT will require additional government input and improvements to the national and provincial agricultural extension system (Chen et al., 2014; Hu, Yang, Kelly, & Huang, 2009). Especially under the climate change and increasing food demand with limited resources, the investment in agronomic research that incorporates the ecosystem perspective across disciplinary and institutional boundaries would be necessary to the large-scale technology extension to positively better the ecological system and improve economic performance of crop production (Chen et al., 2014; Xia et al., 2017). Such efforts are vital for achieving sustainable agricultural production in developing countries. This is especially important for countries such as China, which has been experiencing severe environmental degradation and pollution of its soil and water systems.

The overuse of nitrogen fertilizer has been a series problem and nitrogen fertilizer management technology to improve the efficiency is an important topic for the academic society. The demand for impact assessment research is high due to the large share of resources devoted to natural resource management and the research could guide the future studies with a rigorous evaluation (Yamano et al., 2016). The successful story of TCT adoption in China provides a good example for the countries encountering overuse of fertilizer with environment cost.

Besides, fertilizer deficiency also exists in many developing countries and agricultural technology to reduce the nitrogen input is required. The adoption of TCT would be beneficial for the resource-poor farmers because the cost could be saved with nitrogen efficiency improvement. As the economic growth and agricultural input increasing, a wide extension of TCT would be helpful for the developing countries to avoid the challenge between maintaining food security and addressing environmental problems, so that the agriculture to achieve sustainable development.

Note

1. Because the rice lodging rate is mainly related to the weather, the coefficient on TCT adoption was not significant

in the late rice lodging rate model (Table 3, column 5, rows 1 and 2). Lodging normally occurs during the early season, when typhoons and rain are more common. Lodging during the late season is rare in Guangdong Province.

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