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Maize yield and nitrogen-use characteristics were promoted as consistently improved soil fertility: 6-year straw incorporation in Northeast China

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Abstract: Long-term impacts of straw incorporation on soil fertility, and maize production and nitrogen (N) use status had not been thoroughly investigated in Northeast China, the most vital agricultural base across the nation. We conducted a consecutive 6-year field experiment, including straw amendment at 4 000, 8 000 and 12 000 kg/ha, and no straw incorporation was set as the control. Our experiment confirmed that the grain yield and crop N uptake in straw treatments were raised due to consistently improved soil fertility indices (associated with soil N cycling), and larger straw addition generally exerted more profound influences. Boosted nitrogen harvest index (NHI) indicated that nitrogen use efficiency (NUE) was gradually enhanced if applying more straw. More specifically, greater straw amendment caused higher N recovery efficiency from straw N, even though the N recovery efficiency of accumulated N addition declined accordingly (considering fertiliser N besides straw N). Thus, these trends suggested that more efficient utilisation of straw N by crop was the probable reason for elevated NUE over multi-year time series. Our research offered helpful insight to optimally employ straw incorporation and N fertilisation for coordinating agricultural sustainability and environmental protection.

Keywords: soil property; field management; soil nutrient; environment-friendly agriculture; *Zea mays* L.

China is the world's largest grain producer, and the production of crop straw was estimated up to about 1 billion tons per year, accounting for about one-third of the global production (Li et al. 2017). Removing crop straw from the field would inevitably deteriorate the soil quality due to exhausted soil nutrients year by year. In order to stabilise high crop yield, Chinese farmers were used to applying large amounts of mineral nitrogen (N) fertiliser instead of organic fertiliser (such as crop straw), further lowering the soil quality and leading to environmental pollution due to the loss of excessive N (emitted to water or atmosphere). Making full use of harvested straw was believed to be the foundation for realising sustainable and environment-friendly agriculture in China (Liu et al. 2014, Li et al. 2018).

Inputting the straw back to the field has been interestingly regarded as a promising field practice, as it can support higher crop productivity as a result of replenished soil fertility, bolstered soil physical properties and reduced crop water consumption (Qi et al. 2019). Soil nutrient indices (especially soil microbial properties) are generally monitored to capture and compare the performances of field practices on soil quality, as they play vital roles during soil nutrient cycling. On the other hand, straw

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incorporation could stimulate crop N uptake and meanwhile improved the N use efficiency (NUE) (Miller et al. 2009, Liu et al. 2010). From the crop perspective, the nitrogen harvest index (NHI) could reflect crop N use strategy and NUE (Cheng et al. 2007). However, mechanisms underlying the relative contribution of added straw N to increased NUE needed to be explored (Xu et al. 2020); how NHI was changed after the straw amendment was also under debate (Asibi et al. 2019).

Although the positive effect of straw addition on soil fertility and productivity had been widely reported, numerous studies pointed out that straw incorporation displayed minor influences or even exerted a negative role. These conflicting outcomes might be related to different soil types and climatic conditions, but one of the most important reasons was that available soil N would be immobilised by added straw in the initial period, which subsequently limited crop yield and N uptake. This phenomenon was expected to depend on the amount of incorporated straw (Malhi et al. 2011). Meanwhile, the time spent in previous researches was usually too short to mirror the cumulative effects of straw incorporation on crop yield, N usage and soil fertility, because these immobilised N could be ultimately utilised by crop through remineralisation undergo multi-year period (Dourado-Neto et al. 2010). To the best of our knowledge, employing a relatively long-period experiment subjected to different amounts of straw incorporation to detect gradual changes of soil properties and elucidate the simultaneous variations of crop yield and N use features was urgently required.

Northeast China, which ranked first for crop production across the nation, was called as "bread basket of China". However, due to the long-term history of intensive agricultural activity, the deterioration of soil quality and associated crop yield suppression posed a great threat to the food security of the whole country. This region also possessed the characteristic of a large surplus of crop straw. Consequently, it was very necessary to uncover and differentiate the relative contribution of straw return on soil properties and crop performance in Northeast China. As the single maize cropping system was the dominant system in Northeast China, we monitored the impacts of 6-year continuous straw return on maize productions based on an *in-situ* field experiment located in the typical area of Northeast China. The purpose of this research was undertaken to (1) characterise the multi-year trends of soil nutrient and soil microbial parameters; (2) evaluate the effects of straw incorporation on maize productivity and crop N uptake; (3) analyse crop N use feature induced by straw amendment.

MATERIAL AND METHODS

Study site. This experiment was done at Shenyang Experimental Station, which was located at 41°32'N latitude and 123°23'E longitude. This site featured a typical monsoon climate. The mean annual temperature is 7.5 °C with a maximum of 39.3 °C in July and a minimum of –33.1 °C in January. The precipitation mainly occurred from May to September, with the mean annual precipitation of about 500 mm. The soil in this study site belongs to an Alfisol, a typical soil group for agricultural production in the region.

Experimental design and field management. In this research, four levels of the straw amendment were (0, 4 000, 8 000 and 12 000 kg/ha) marked as CK, S_4, S_8 and S_{12}, respectively. Each experiment plot was 7.2 m^2 (1.8 m × 4 m), and all 16 plots (4 × 4) were arranged in a randomised block design with the four replicates and protective zones with a width of 1 m between each plot were set up. In each plot, the row spacing of maize was arranged at 60 cm, and the plant was sown at 25 cm intervals according to the regional recommendation (about 66 000 plants/ha). More detailed information about the experiment was displayed in our previous paper (Jiang et al. 2017).

The trial was initiated in the October of 2009. The maize cultivar of Dongdan 72 was always used. In every October after maize harvest, chopped maize straw was spread uniformly on the surface of the soil and then manually mixed into the soil with spades to into the top 20 cm soil. The same manner without straw addition was done in CK treatment. The nutrient statuses of maize straw used for this experiment were analysed every year, with the mean value of 6.86, 0.63 and 4.68 g/kg for N, P and K content across the 6 years. During the growing season of next year, the identical dose of inorganic fertilisers was applied in each treatment (150 kg/ha/year for N in the form of urea and 39.6 kg/ha/year for P in the form of calcium superphosphate). P was incorporated into the soil before sowing as basal fertilisers, and N was applied three times during the growing season according to the development of the plant (at seeding, jointing, and booting stage, respectively), with a ratio of 3:4:3.

Sampling and analysis methods. Crop and soil were sampled during the harvest season from 2010

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to 2015. Five replicated soil samples (0–20 cm depth) were randomly collected from each plot using a metal ring. After removing all visible organic debris and soil fauna, these samples were mixed into one sample for each plot. The crops in each plot were all sampled when reaching maturity, which was divided into grain and straw. The crop samples were oven-dried to a constant weight to evaluate the crop yield. Crop and soil properties were analysed according to the description of Lu (2000). In brief, soil organic carbon (SOC) and total nitrogen (TN) were measured by the potassium dichromate volumetric method and half trace Kjeldahl method, respectively. Soil available nitrogen was converted to NH_4^+ under alkaline conditions, collected in H_3BO_3 solution, and then determined by titration with standard H_2SO_4. The microbial biomass carbon (MBC) and nitrogen (MBN) were determined using the fumigation-extraction method.

Calculation. Based on the application of cumulative N fertiliser (including mineral N and straw N) and the crop N uptake across the 6-year experiment, crop N use features were described using the following parameters: N recovery efficiency of accumulated N addition (NRE_{ac}, %), N surplus (kg N/ha), the proportion of crop N uptake from straw (PNU_{straw}, %) and N recovery efficiency from straw (NRE_{straw}, %) (Liu et al. 2010):

$$NRE_{ac} = \sum_i U_{crop} \Big/ \sum_i F_{in} \quad (1)$$

$$N\ surplus = \sum_i (F_{in} - U_{crop}) \quad (2)$$

$$PNU_{straw} = \sum_i (U_s - U_{ck}) \Big/ \sum_i U_s \quad (3)$$

$$NRE_{straw} = \sum_i (U_s - U_{ck}) \Big/ \sum_i F_s \quad (4)$$

where: U_{crop} – whole crop N uptake by (grain plus straw) for with and without added straw treatments; while U_s – total N uptake by crop in straw addition treatments (kg N/ha); U_{ck} – total N uptake by crop with no straw application (kg N/ha); F_{in} – total amount of applied N (including mineral N and straw N) (kg N/ha); F_s – amount of applied N derived from straw (kg N/ha); i – duration of experimental year (6 years in the present research).

Statistical analysis. The parameters for different straw addition treatments were compared by the SPSS V13.0 (SPSS, Chicago, USA). One-way ANOVA with Duncan's *HSD* (honestly significant difference) test was used to detect the difference of the tested parameters among straw incorporation treatments at the level $P < 0.05$.

RESULTS AND DISCUSSIONS

Straw incorporation altered soil property conditions. SOC and TN for CK were relatively stable across the 6-year period. On the contrary, the values in added straw treatments were gradually increased, indicating the benefits of straw return of SOC and TN were cumulative (Figure 1A, B). More SOC was accumulated by straw incorporation treatments, in the order of $S_{12} > S_8 > S_4 >$ CK (Figure 1A). Similarly, straw incorporation favoured the accumulation of soil TN (Figure 1B). The available soil nitrogen was elevated with an increasing straw incorporation rate, and the impacts were closely related to the duration of the research. In 2010, no statistical changes of soil available nitrogen were identified among CK, S_4 and S_8, while significantly pairwise alterations among the four treatments occurred ($P < 0.05$) in 2015 (Figure 1C). Straw addition dramatically stimulated MBC and MBN, and larger inputted straw usually posed more profound impacts (Figure 1D, E).

The SOC and TN content are the primary parameters that determine soil fertility and sustainable productivity of agro-ecosystems. In previous meta-analyses across the world (Liu et al. 2014) and nation (Lu 2015), the increased magnitudes of SOC and TN were summarised in the range of 7–13.3% and 8.8–14.8%, respectively. The average responses of SOC and TN over a 6-year experiment (17.6% for SOC and 13.9% for TN) were at the high end of values of the above syntheses that embracing various climate and land use types. The possible reasons were low temperature in Northeast China and relatively greater clay content in the soil of our site, which helps to stabilise and accumulate SOC and TN as discussed in our previous researches (Jiang et al. 2017, Jiang and Yu 2019). Interestingly, we found that there was a nonlinear increase of SOC, in which abruptly greater SOC was preserved since the fourth experimental year. This phenomenon had not been recorded to the best of our knowledge, which inspired future studies to trace the transformation SOC that utilising recently developed conceptual guidelines and analytical techniques (Liang et al. 2017).

Straw incorporation significantly improved available soil nitrogen, and this was the nutrient base for boosted crop yield and N uptake (Wei et al. 2015). Soil microbes regulated soil organic matter decomposition and soil nutrient cycling, exerting essential roles in maintaining sustainability and functioning of agro-ecosystem. MBC and MBN were stimulated by

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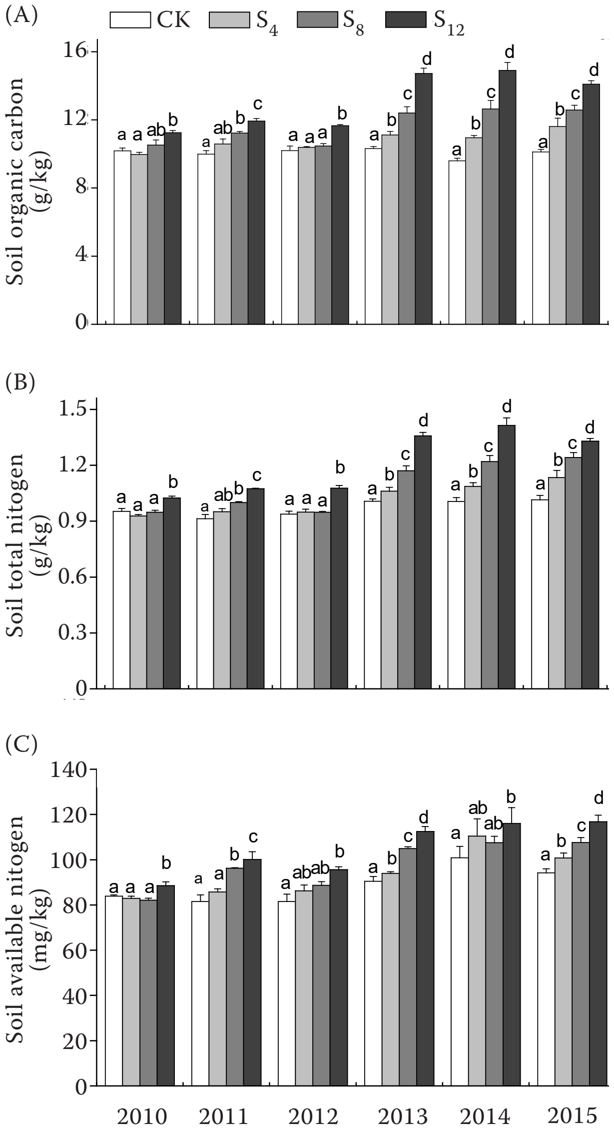

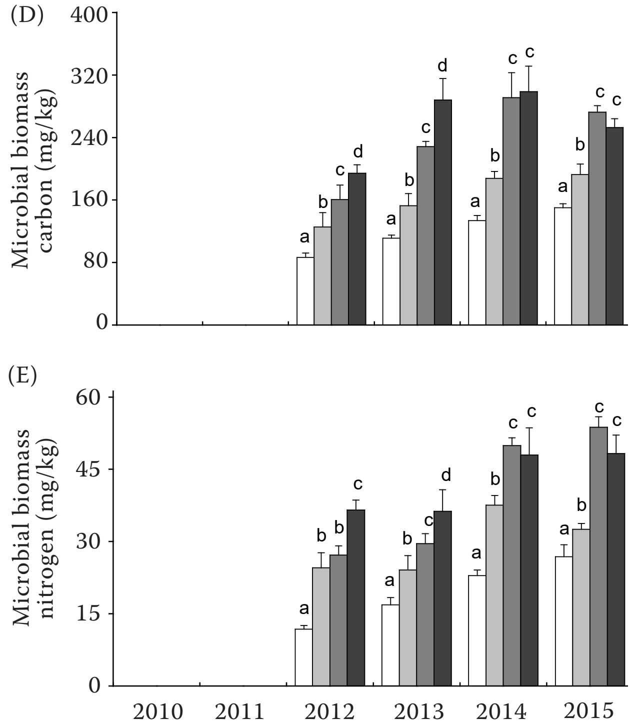

Figure 1. Change of (A) soil organic carbon; (B) soil total nitrogen (N); (C) soil available N; (D) soil microbial biomass carbon (MBC) and (E) nitrogen (MBN) under different straw incorporation treatments in the maize field of Northeast China from 2010 to 2015. Values are means ± standard error. CK – no straw addition; straw amendment at a level of: S_4 – 4 000, S_8 – 8 000, S_{12} – 12 000 kg/ha. Different lower-case letters indicate significant differences (P < 0.05) in the same year. Due to the limitation of experimental site conditions, MBC and MBN were not determined in 2010 and 2011

straw addition in our case. These results were because organic residues can provide substantial nutrients for microorganism growth and reproduction (Zhao et al. 2019). Although MBC and MBN were not measured in the first two years, the marked response of MBC and MBN appeared earlier (since 2012), and the influences were proportionately much greater than other soil parameters. This result corroborated the proposal that MBC and MBN were more sensitive indices for indicating soil fertility changes as they reflected "early warming" of soil state transitions during which other parameters might take many years to become measurable (Powlson et al. 2011).

Straw incorporation favoured maize yield and crop N uptake. Maize grain yield and crop N uptake largely varied among the 6-year experimental period, probably resulting from impacts of local meteorology factors. The straw returning always had positive effects on grain yield crop N uptake, manifesting this tendency of $S_{12} > S_8 > S_4 >$ CK (Table 1). On average, straw addition greater than 4 000 kg/ha statistically increased (P < 0.05) grain yield and crop N uptake compared to the CK. Furthermore, NHI displayed an increasing trend as more straw was applied (Table 2), among which the differences between S_{12} and CK in most of the experimental year and the 6-year mean of these two values were statistically significant (P < 0.05).

Generally, straw addition is conducive to crop yield and nutrient uptake, in line with the global meta-analysis (Liu et al. 2014). However, the influenced direction and magnitude were depended on experiment duration, added straw amount, applied N level and local conditions. Malhi et al. (2006) reported that the stimulating effects of straw on crop

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Table 1. Comparison of grain yield and plant nitrogen (N) uptake among straw incorporation treatments from 2010 to 2015

	Treatment	2010	2011	2012	2013	2014	2015	Mean of the 6 years
Grain yield (kg/ha)	CK	6 321^{a}	10 011^{a}	6 526^{a}	7 922^{a}	8 479^{a}	7 033^{a}	7 716^{a}
	S_4	6 513^{b}	10 375^{b}	7 867^{b}	8 033^{a}	8 972^{b}	7 208^{a}	8 161^{a}
	S_8	6 570^{b}	10 153^{ab}	7 759^{b}	8 380^{b}	9 267^{c}	7 967^{b}	8 349^{b}
	S_{12}	7 799^{c}	10 942^{c}	8 525^{c}	8 780^{c}	9 642^{d}	8 788^{c}	9 079^{c}
Plant N uptake (kg N/ha)	CK	120.2^{a}	176.6^{ab}	106.7^{a}	148.0^{a}	128.1^{a}	109.9^{a}	131.6^{a}
	S_4	123.4^{b}	173.4^{a}	121.8^{b}	140.1^{a}	126.4^{a}	123.1^{b}	134.7^{a}
	S_8	131.9^{c}	184.3^{b}	130.8^{c}	153.2^{b}	138.3^{b}	124.9^{b}	143.9^{ab}
	S_{12}	145.1^{d}	177.3^{ab}	151.5^{d}	154.6^{b}	150.6^{c}	134.5^{c}	152.3^{b}

CK – no straw addition; straw amendment at a level of: S_4 – 4 000, S_8 – 8 000, S_{12} – 12 000 kg/ha. Values within a column for the same year followed by different letters denote significant difference ($P < 0.05$) among treatments

yield and N uptake were only recorded in years with below-average precipitation. Other researchers found that the negative effect of straw disappeared when accompanied by the input of a high level of mineral N (above 120 kg N/ha) (Agenbag et al. 1998). In our case, the grain yield and N uptake were consistently elevated by straw additions from the beginning of the experiment. The increased magnitude was more dramatic if using more straw (Table 1). These results were probably because that the quantity (150 kg N/ha) and mode (split into three times over one growing season) of applied N fertiliser alleviated the competition of available soil N between crop root and soil microbes (Xu et al. 2018). Consequently, this practice was strongly recommended to be adopted in Northeast China. Furthermore, the benefits of added straw treatment became larger with the progress of the experiment, in agreement with the dynamics of soil fertility indices, which further corroborated that straw return could favour the sustainability of crop production (Liu et al. 2014). On average, of our data set, the relative increases of grain yield and crop N uptake were almost comparable. This phenomenon suggested that N and the factors other than N should be equally focused on for maize production under present management conditions.

This index of NHI was believed to reflect the crop NUE, and greater NHI in our case demonstrated there was enhanced NUE for maize with increased use of straw (Cheng et al. 2007, Asibi et al. 2019). Generally, viewpoint-based on one growing season study emphasised that higher crop NUE in straw addition treatment could be attributed to the N immobilisation-mineralisation process, and this process reduced the unnecessary loss of the non-straw-derived N from N fertiliser (Cao et al. 2018) whether the N originating from straw exerted a role over long-term period needed further exploration (see next section).

The characteristics of N utilisation across the multiple-year experiment. The N utilisation characteristics were deeply affected by the 6-year straw incorporation treatments. The values of NRE_{ac} ranged from 87% to 62%, which was markedly reduced with the increased use of straw ($P < 0.05$) (Figure 2A). Correspondingly, more straw caused a significantly greater N surplus, varying from 116 kg/ha to 523 kg/ha (Figure 2B). According to the difference method, the crop N use directly originating from straw was

Table 2. Comparison nitrogen harvest indexes (NHI) among straw incorporation treatments from 2010 to 2015

	Treatment	2010	2011	2012	2013	2014	2015	Mean of the 6 years
NHI	CK	0.68^{a}	0.75^{ab}	0.72^{a}	0.63^{a}	0.71^{a}	0.69^{a}	0.697^{a}
	S_4	0.68^{a}	0.74^{a}	0.74^{b}	0.64^{ab}	0.73^{ab}	0.70^{a}	0.705^{a}
	S_8	0.67^{a}	0.74^{a}	0.72^{a}	0.64^{ab}	0.77^{b}	0.70^{a}	0.707^{a}
	S_{12}	0.73^{b}	0.77^{b}	0.74^{b}	0.66^{b}	0.75^{ab}	0.74^{b}	0.732^{b}

CK – no straw addition; straw amendment at a level of: S_4 – 4 000, S_8 – 8 000, S_{12} – 12 000 kg/ha. Values within a column for the same year followed by different letters denote significant difference ($P < 0.05$) among treatments

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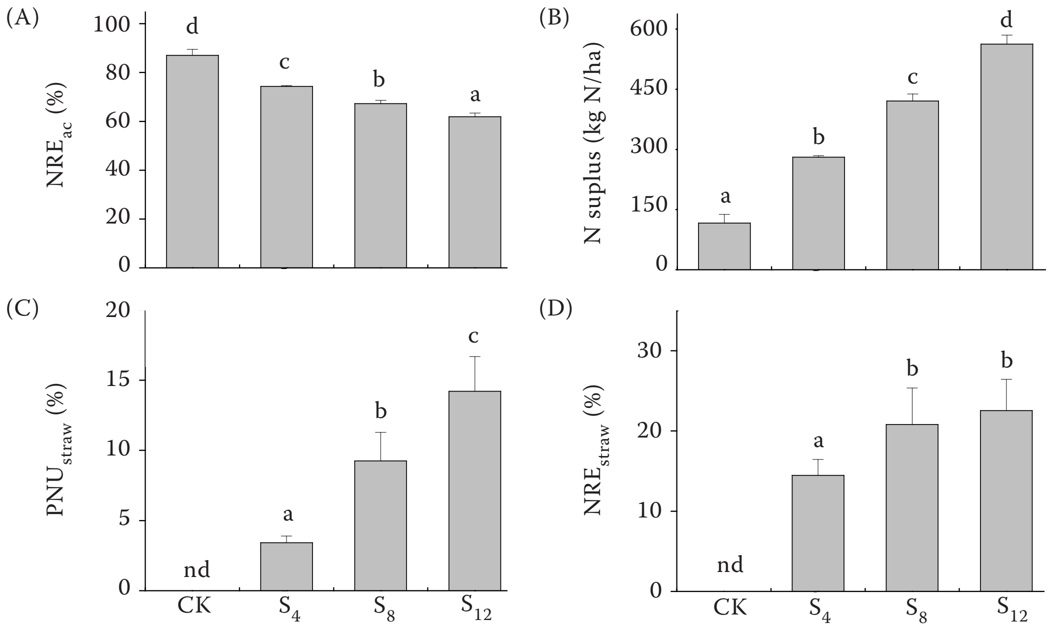

Figure 2. The balances and features of crop nitrogen (N) utilisation as affected by different straw incorporation treatments. The parameters were computed following 6-year accumulations (2010 to 2015). The N recovery efficiency of (A) accumulated N addition (NRE_{ac}) and (B) N surplus took the entire N fertiliser (including mineral N and straw N) into account; while the proportion of (C) crop N uptake from straw (PNU_{straw}) and (D) N recovery efficiency from straw (NRE_{straw}) were determined by difference method. The detailed calculations were listed in Eqs. 1–4. nd – no data. Values are means ± standard error. CK – no straw addition; straw amendment at a level of: S_4 – 4 000, S_8 – 8 000, S_{12} – 12 000 kg/ha. Different lower-case letters indicate significant differences (P < 0.05)

estimated. PNU_{straw} was gradually raised with the increasing level of straw addition (Figure 2C), and the magnitudes of NRE_{straw} for high straw incorporation (S_8 and S_{12}) was statistically more significant than S_4 (P < 0.05), with the value of 14, 21 and 23% for S_4, S_8 and S_{12}, respectively (Figure 2D).

NRE_{ac} was markedly reduced with the increased use of a straw. Apparently, the explanation was that more straw addition would lead to a greater potential for N immobilisation, and thus the more N remained in soil (Miller et al. 2009). The N surplus accordingly exhibited a significantly increased trend. These remaining N in the soil were expected to replenish native soil N pool through complex N stabilisation processes under a long-term period, which would be continuously utilised by subsequent crops (Dourado-Neto et al. 2010). This was the foundation for sustainable agricultural practices. To distinguish the direct effect of straw N on crop N utilisation, the difference method was used to calculate the NRE_{straw}. In contrast to the change of NRE_{ac}, NRE_{straw} showed an increasing pattern if more straw was incorporated, following the change of NHI (indicating more straw input led to greater NUE). This underlying connection within our data set hinted that high efficient use of straw N might contribute to enlarged crop NUE across the multiple-year period. These results enriched our understanding of greater NUE caused by straw incorporation and shed additional light on optimum utilisation of straw N. However, our explanation faced some uncertainties. We had not tracked the real fate of straw N, considered the priming effect of added straw and compared the amelioration of soil constraints other than N. Future research should employ ^{15}N-labelled straw and a more complicated experimental design (Dourado-Neto et al. 2010, Celestina et al. 2019). The above approaches would provide more solid evidences and reveal detailed mechanisms responsible for the impact of straw incorporation on crop productivity and N usage.

In conclusion, a consecutive 6-year straw incorporation experiment was conducted to clarify and optimise the environmental-friendly strategy for maize production in Northeast China. Straw addition could not only raise grain yield resulting from ameliorated soil property but also improve maize NUE simultaneously. The long-term data set further indicated that high efficient use of straw N by plant might be a potential mechanism for the elevated NUE. Although detailed mechanisms were

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needed to be uncovered using the more precise and complicated method, our study provided great implication for farm operators and policy-makers to make full use of a large amount of straw in Northeast China for enhancing agricultural productivity and sustainability, and meanwhile improving environmental protection.

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