

## EFFECT OF STRAW SUBSTITUTING PARTIAL MINERAL N FERTILIZER ON N DISTRIBUTION OF MAIZE PLANTS AND SOIL IN NORTHEAST CHINA

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**Abstract.** Reducing mineral N fertilizer application rate and improving N use efficiency is important for sustainable agriculture. Whether straw return could substitute partial mineral N fertilizer in the applying year is still not conclusive in the case of spring corn planting in Northeast China. This work was conducted to investigate the optimal substitution rate through a field experiment with no fertilization (CK), 100% mineral N (IF), 25%/50%/75%/100% straw application combined with reduced mineral N fertilizer (S25/ S50/ S75/ S100) at a total of 240 kg N/hm<sup>2</sup> application rate in Jilin Province, Northeast China. The results showed that there was no significant difference in corn yield between straw application treatments and IF except for S100, which was 11.1% lower. Compared to IF, corn straw application did not affect N uptake amount and nitrogen harvest index ( $p > 0.05$ ), while S75 obviously increased N use efficiency by 29.6%. Straw application decreased NO<sub>3</sub><sup>-</sup>-N content and resisted downward migration in the soil profile. In conclusion, integrated application of 75% corn straw with reduced mineral N fertilizer at a total of 240 kg N/hm<sup>2</sup> was a reasonable fertilization practice as it reduced NO<sub>3</sub><sup>-</sup>-N content and prevented leaching in soil profile as well as increased N use efficiency without negative effect on corn yield.

**Keywords:** *yield, equal N application rate, NH<sub>4</sub><sup>+</sup>-N, NO<sub>3</sub><sup>-</sup>-N, nitrogen use efficiency*

### Introduction

Nitrogen, as one of the three essential nutrient elements for crop production, plays an important role in the growth of stems, leaves and grains as it is the main component of protein. In order to obtain high crop yield, enough nitrogen should be supplied to plants during their growth. Mineral nitrogen is extensively used for crop production worldwide and urea is the most commonly used in China (Zhu et al., 2002). While sufficient application of mineral nitrogen fertilizer increases crop yield and quality, its negative impacts on the environment have been documented, such as soil acidification and compaction (Guo et al., 2010; Cai et al., 2015), eutrophication of surface water (Zhang et al., 2011), contamination of groundwater (Hillin et al., 2003; De Paz et al., 2004), accelerating global warming by greenhouse gases emission (Galloway et al., 2003; Battye et al., 2017).

Spring corn is one of the dominant crops in Northeast China, where one third of corn grains in China is produced. The most common fertilization practice in this area is to use 100% mineral N fertilizer. During 1980 to 2010, the application rate of nitrogen for corn in this area has been steadily growing from 100 kg N/hm<sup>2</sup> to more than 300 kg N/hm<sup>2</sup> (Gao et al., 2010), while the nitrogen use efficiency dropped from 52.6% to 20% (Zhang

et al., 2008; Cui et al., 2008; Zhi et al., 2020) and its adverse effect has been observed. However, what concurrently happening is less applying organic fertilizer such as animal manure and straw in farmland mainly due to the inconvenient application of such materials.

As planting area and grain yield of corn is growing steadily in Northeast China, corn straw is also rising in recent years. In 2015, the total corn straw yield in Northeast China was 159 million tons, accounting for 19.2% of the national straw output (Li et al., 2017a). How to dispose such large amount of straw in a short-term is still a challenge to local farmer since the low temperature and humidity of soil makes decomposition process slow. In the past several decades, most of corn straw was burnt after harvest or before sowing, which resulted in the loss of organic matter reduced to soil as well as serious air pollution. In order to solve these problems and improve the fertility of black soil, conservation tillage which includes less or no tillage combined with straw application has been recommended. Numerous studies have proved that straw application could improve soil fertility, water holding capacity and carbon sequestration (Liu et al., 2014; Li et al., 2016).

Compared with mineral fertilizer, corn straw has lower N concentration and slower releasing rate, which greatly increases N use efficiency and reduces N loss via farmland runoff. Furthermore, the application of crop straw in farmland soil also alleviates the issue of wastes disposal in corn production. Thus, straw application combined with mineral fertilizer has been recommended by many scientists in recent years (Rasool et al., 2008; Lu et al., 2009; Demelash et al., 2014; Zhang et al., 2015).

As discussed above, corn straw application is beneficial for soil and crop growth. While one remarkable thing is that the results were obtained on the base of the constant amount of mineral N fertilizer combined with more corn straw (Wang et al., 2018a; Afreh et al., 2018). Few researches were carried out on equally total nitrogen application amount (organic N + mineral N) on spring corn in Northeast China. So, there is little knowledge about whether corn straw application could substitute partial mineral N fertilizer. In addition, many long-term experiments have been taken to evaluate the effect of corn straw on soil properties and crop growth after several years of application (Wang et al., 2018b; Xu et al., 2019). However, its temporal influence was seldom estimated in the fertilization year, which might bring some undesirable negative impacts on yield and soil environment.

In this paper, integrated various ratio of corn straw to mineral N fertilizer at an equally total N application rate of 240 kg N/hm<sup>2</sup> was studied in the fertilization year to evaluate its effect on (1) corn yield, (2) nitrogen uptake characteristics of corn plants in different growth stage, (3) nitrate, ammonium distribution in the soil profile (0-100 cm). We assumed that an appropriate ratio of straw application could substitute partial mineral N fertilizer characterized by higher N use efficiency, less NO<sub>3</sub><sup>-</sup>-N content and leaching in soil profile without negative effect on corn yield.

## Material and Methods

### *Field experimental site and design*

Field work was conducted at the experimental station of Jilin Agricultural University (43°49'6.6"N, 125°23'56.4"E), which lies in Changchun City, Jilin province in Northeast China. It is a continental monsoon climate with an average annual rainfall of 582 mm (more than 60% of the rainfall occurs during June to August) and average annual temperature of 5.5°C. The sunshine time is 2688 hours per year and the annual average

effective accumulated temperature is 2900°C. The frost free period is 132 days per year. The soil is classified as phaeozems according to FAO soil taxonomy, and maize has been planted at least 20 years without straw return. Analyses indicated pH, organic matter, total N, available N, P and K of the top 0-20 cm soil was 6.89, 27.4 g/kg, 1.26 g/kg, 150.7 mg/kg, 31.2 mg/kg, 136.1 mg/kg, respectively.

The field work was done in 2015 with six treatments (*Table 1*) and three replicates in a randomized complete block design. Each plot was 58.5 m<sup>2</sup> (6.5 m×9 m) with 2 m wide of buffering strip around it. 25%, 50%, 75%, 100% straw application was set and the rest N, P, K was supplied by mineral fertilizer after nutrients in straw was subtracted in order to maintain the totally same rates of 240 kg N /hm<sup>2</sup>, 154 kg P<sub>2</sub>O<sub>5</sub>/hm<sup>2</sup> and 197 kg K<sub>2</sub>O /hm<sup>2</sup>. Corn straw was taken from other field with Nitrogen (N), phosphorus (P), potassium (K) and moisture contents of 0.72%, 0.25%, 1.50%, 30%, respectively, and crushed into 2-5 cm length before applying. 100% straw application amount was determined by grain yield of 12000 kg/hm<sup>2</sup> and the ratio of grain to straw was 1: 1.2, which was a relatively higher output in local area. The fertilizers were urea (N 46%), diammonium (N 18%, P<sub>2</sub>O<sub>5</sub> 46%) and superphosphate (P<sub>2</sub>O<sub>5</sub> 46%), potassium chloride (K<sub>2</sub>O 60%), which were products of DQL chemical fertilizer Co., Ltd, China and Yuntianhua Co., Ltd, China. The fertilization detail of each treatment was listed in *Table 1*.

**Table 1.** Details of fertilization in each treatment (kg/hm<sup>2</sup>)

Treatment code	Treatment	Organic material				Mineral fertilizer		
		Rate	N	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O	N	P <sub>2</sub> O <sub>5</sub>	K <sub>2</sub> O
CK	-	0	0	0	0	0	0	0
IF	100 % mineral N	0	0	0	0.0	240.0	154	197
S25	25% maize straw+ mineral N	3600	18.1	6.3	37.8	221.9	147.7	159.2
S50	50% maize straw+ mineral N	7200	36.2	12.6	75.6	203.8	141.4	121.4
S75	75% maize straw+ mineral N	10800	54.3	18.9	113.4	185.7	135.1	83.6
S100	100% maize straw	14400	72.4	25.2	151.2	167.6	128.8	45.8

Note: CK represented no fertilization treatment, IF represented merely mineral N fertilization treatment, S25/ S50/ S75/ S100 delegated 25%/ 50%/ 75%/ 100% corn straw return + remaining N supplemented by mineral N

Corn (*Zea mays* L.) hybrid variety XY335 was sowed at one seed per hole with the planting density of 6.5×10<sup>4</sup> plants/hm<sup>2</sup> on 3 May 2015. All mineral P and K fertilizers, 40% mineral N fertilizer and all straw were mixed with top 20 cm soil before sowing as basal fertilizer. A half of the rested mineral N fertilizer was applied at the beginning of stem elongation and the other half was applied at inflorescence emergence as top dressing after sample collection. The seeds were sowed after plough, and there was no other tillage during maize growth. It was rain-fed agriculture and no irrigation was given. Weeds were controlled by applying herbicides (atrazine and acetochlor). Corns were harvested on September 29, 2015.

### **Field investigation and sample collection**

One week after seed germination, number of plants in the whole plot was counted to calculate the germination rate. The plant was sampled in leaf development, early stem elongation, 9 or more nodes detectable, tassel emergency, early grain development, early milk, early ripening and fully ripening stage, which corresponded to 18, 47, 64, 76, 96,

111, 121 and 131 days after germination, respectively. Soil samples were simultaneously taken in tassel emergency and fully ripening stage.

Representative 3-5 plants were sampled in each plot at each sampling time, washed in deionized water, separated into leaf, stem, ear and grain, oven-dried at 105°C for 20 min, followed by drying at 65°C until the weight was constant. Then, the plants were crushed and sieved for further analysis. For the last sampling stage, plants in 10 m<sup>2</sup> in the middle of each plot were harvested manually to calculate the grain yield on the basis of 14% moisture content and to determine grain yield components of 1000-grain weight, rows per ear, grain number per row, grain number per ear. No-ear plants were counted in the whole plot.

The soil of 0-100 cm depth was taken from each plot using a soil probe, and divided into 5 subsamples at each 20 cm depth. The surface litter was removed before sampling and 3 sites in each plot were randomly taken and then mixed. The soil samples were put into self-sealing plastic bags and brought to lab, stored at -20°C for nitrate and ammonium analysis.

### **Sample analysis**

The total N concentration of plants was analyzed by a micro- Kjeldahl procedure after digested by H<sub>2</sub>SO<sub>4</sub>-H<sub>2</sub>O<sub>2</sub> (Nelson et al., 1973). The concentration of ammonium and nitrate was measured by continuous flow analyzer (SEAL AutoAnalyzer 3-AA3, Bran and Luebbe, Germany) after being extracted by 2 mol/L KCl (López Pasquali et al., 2007).

### **Data processing**

$$\text{NUE} = \frac{N_f - N_{ck}}{F} \times 100\% \quad (\text{Zhang et al., 2008}) \quad (\text{Eq.1})$$

$$\text{NHI} = \frac{G_N}{TP_N} \quad (\text{Afreh et al., 2018}) \quad (\text{Eq.2})$$

$$\text{NAE} = \frac{Y - Y_0}{F} \quad (\text{Afreh et al., 2018}) \quad (\text{Eq.3})$$

NUE (%) is nitrogen use efficiency, N<sub>f</sub> is the nitrogen uptake by plant in fertilization treatment, N<sub>ck</sub> is the nitrogen uptake by plant in control, F is the application amount of mineral N fertilizer, NHI is nitrogen harvest index, G<sub>N</sub> is the grains nitrogen uptake, TP<sub>N</sub> is the total nitrogen uptake by plant, NAE (kg/kg) is nitrogen agronomic efficiency, Y is the grain yield in fertilization treatment, Y<sub>0</sub> is the grain yield in control.

The data were analyzed using SPSS Statistics 17.0 (SPSS, Inc., Chicago, IL, USA), and differences between treatments were compared by the method of least significant difference (LSD) test at the 0.05 level. Microsoft Excel 2016 was adopted for calculating and drawing.

## **Results**

### **Grain yield and its components**

Corn grain yield and its components are indicated in *Table 2*. The results showed that treatments significantly affected germination rate, 1000-grain weight, grains per ear and grain yield ( $p < 0.05$ ).

**Table 2.** Germination rate and grain yield components of corn in different fertilization treatments

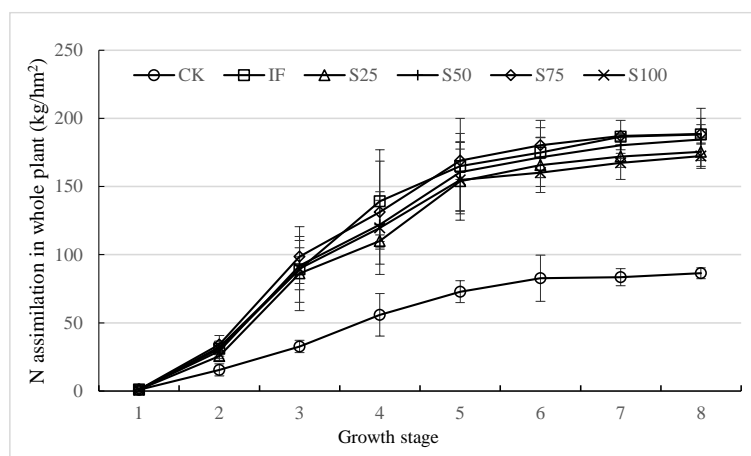
Treatment	Germination rate (%)	No-ear Ratio (%)	1000-grain weight (g)	Rows per ear	Grains per ear	Grain yield (kg/hm <sup>2</sup> , DW)
CK	94.9 ± 1.3 a	9.8 ± 1.3 a	228.3 ± 23.6 e	16.1 ± 0.6 ab	505.4 ± 97.8 c	5654 ± 666 c
IF	92.5 ± 1.0 b	5.9 ± 3.5 b	339.7 ± 12.7 ab	16.3 ± 0.3 a	662.5 ± 25.8 ab	8357 ± 189 a
S25	93.2 ± 1.3 b	0.7 ± 1.3 c	315.3 ± 2.7 abc	16.3 ± 0.1 a	574.4 ± 49.3 bc	8175 ± 123 ab
S50	93.7 ± 3.1 b	1.5 ± 1.3 c	303.1 ± 37.5 cd	16.4 ± 0.2 a	644.8 ± 36.6 ab	8235 ± 534 a
S75	89.9 ± 2.5 c	3.4 ± 4.2 c	304.6 ± 14.3 bc	16.5 ± 0.6 a	673.7 ± 35.1 a	8402 ± 735 a
S100	80.0 ± 0.8 c	8.0 ± 0.0 ab	349.2 ± 8.7 a	14.1 ± 1.5 b	565.5 ± 58.9 ab	7432 ± 232 b

Note: Different letters in the same column signified significant difference at  $p < 0.05$ . CK represented no fertilization treatment, IF represented merely mineral N fertilization treatment, S25/ S50/ S75/ S100 delegated 25%/ 50%/ 75%/ 100% corn straw return + remaining N supplemented by mineral N

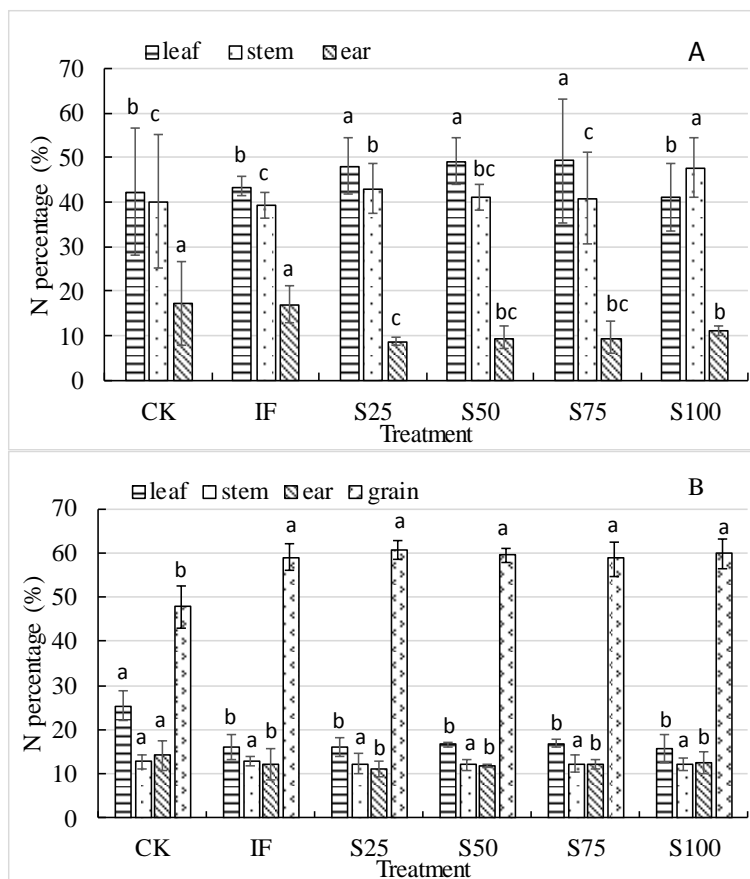
Germination rate in all fertilization treatments was 1.2-14.9% lower than CK and decreased as straw application was increasing with S75, S100 significantly lower than S25, S50 by an average of 8.5% ( $p < 0.05$ ). Appropriate straw application (S25, S50, S75) decreased no-ear ratio by an average of 4.0% compared to IF and 7.9% compared to CK. S100 had an opposite effect on it. Meanwhile, S100 decreased rows per ear by 2.2 and grain yield by 925 kg/hm<sup>2</sup> compared to IF. No significant difference was found for the grain per ear values of different treatments ( $p > 0.05$ ). Grain yield of the 100% mineral treatment was significantly lower than the others ( $p < 0.05$ ).

### Nitrogen accumulation in corn plant

The N assimilation of whole corn plant in different growth stage was showed in *Figure 1*. The tassel emergency stage (represented vegetative stage) as well as fully ripening stage (represented reproductive stage) was selected to analyze N distribution in different plant organ and the results were listed in *Figure 2*.



**Figure 1.** N assimilation amount in whole corn plant during different growth period in different fertilization treatments. Growth stages: 1- leaf development, 2-early stem elongation, 3-9 or more nodes detectable, 4- tassel emergency, 5- early grain development, 6- early milk stage, 7- early ripening and 8- fully ripening. CK represented no fertilization treatment, IF represented merely mineral N fertilization treatment, S25/S50/S75/S100 delegated 25%/50%/75%/100% corn straw return + remaining N supplemented by mineral N



**Figure 2.** N uptake in different plant organ to the total of plant in tassel emergency (A) and fully ripening stage (B). CK represented no fertilization treatment, IF represented merely mineral N fertilization treatment, S25/S50/S75/S100 delegated 25%/50%/75%/100% corn straw return + remaining N supplemented by mineral N

Compared with CK, fertilization significantly increased N assimilation amount by 86.0-102.3 kg/hm<sup>2</sup>, or 99.7%-118.5% in the fully ripening stage. But there was no obvious difference between straw application treatments and IF except for S100 in leaf development stage and early ripening stage, which was significantly lower than IF ( $p < 0.05$ ).

Straw application promoted N accumulating in leaves and stems during vegetative growth as N proportion in leaves for S25, S50 and S75 was obviously higher than other organs during tassel emergency stage. And N proportion in ears increased significantly from 8.8% in S25 to 11.1% in S100. In fully ripening stage, N proportion in leaves decreased from an average of 47.0% in tassel emergency stage to an average of 16.3%, and stems declined from 43.3% to 12.2%. While for ears, it increased from 9.8% to 11.9%. For IF, N in leaves and stems decreased by 27.5% and 26.6%, respectively, which were lower than those of straw application treatments.

### Nitrogen use efficiency

N uptake by plant and relevant indicators are list in Table 3. Compared with CK, N uptake and N harvest index was significantly higher for fertilization treatments. While no significant difference was found for N uptake by plant between IF and the straw

application treatments ( $p > 0.05$ ). The N use efficiency of the S75 was 12.6% significantly higher than IF ( $p < 0.05$ ). No significant difference was observed for nitrogen harvest index and apparent nitrogen recovery ( $p > 0.05$ ) (Table 3), while the N agronomic efficiency of the S100 was significantly lower than the rest four straw application treatment and IF ( $p < 0.05$ ).

**Table 3.** Nitrogen use efficiency of corn in different fertilizer treatments

Treatment	N uptake by plant (kg/hm <sup>2</sup> )	N use efficiency (%)	N harvest index	N agronomic efficiency (kg/kg)
CK	86.3 ± 4.1 b	-	0.45 ± 0.02 b	-
IF	188.2 ± 8.4 a	42.5 ± 3.5 bc	0.51 ± 0.03 a	11.3 ± 0.8 a
S25	175.5 ± 5.0 a	40.2 ± 2.2 c	0.53 ± 0.02 a	11.4 ± 0.6 a
S50	184.6 ± 8.6 a	48.2 ± 4.2 abc	0.52 ± 0.03 a	12.7 ± 2.6 a
S75	188.6 ± 11.6 a	55.1 ± 6.2 a	0.51 ± 0.01 a	14.8 ± 4.0 a
S100	172.3 ± 19.5 a	51.3 ± 11.6 ab	0.52 ± 0.04 a	10.6 ± 1.4 b

Note: Different letters in the same column signify significant difference at  $p < 0.05$ . CK represented no fertilization treatment, IF represented merely mineral N fertilization treatment, S25/ S50/ S75/ S100 delegated 25%/ 50%/ 75%/ 100% corn straw return + remaining N supplemented by mineral N

### Nitrate distribution in soil profile

Nitrate distribution in soil profile is indicated in Table 4. NO<sub>3</sub><sup>-</sup>-N in all straw application treatments were lower than IF in both growth stages, and decreased with soil depth and straw application increasing.

**Table 4.** NO<sub>3</sub><sup>-</sup>-N content in soil profile in different fertilization treatments in tasseling and fully ripening stage (mg/kg)

	Profile	CK	IF	S25	S50	S75	S100
Tassel emergency stage	0-20 cm	3.4 ± 0.9 d	22.6 ± 2.9 a	19.8 ± 1.0 ab	17.5 ± 1.0 bc	16.4 ± 1.1 c	14.5 ± 2.7 c
	20-40 cm	4.0 ± 1.6 d	22.1 ± 5.5 a	19.5 ± 1.6 b	13.1 ± 2.5 c	9.2 ± 0.9 c	10.3 ± 3.0 c
	40-60 cm	3.3 ± 1.1 d	18.1 ± 1.9 a	15.7 ± 3.0 b	10.6 ± 1.8 c	8.9 ± 1.5 c	5.2 ± 1.3 d
	60-80 cm	3.0 ± 0.9 c	12.6 ± 6.6 ab	13.8 ± 1.6 a	11.4 ± 1.7 b	4.5 ± 1.0 c	3.1 ± 0.8 c
	80-100 cm	2.5 ± 0.2 d	13.5 ± 1.0 a	11.5 ± 0.9 b	5.6 ± 1.2 c	3.2 ± 0.3 d	2.7 ± 0.5 d
Fully ripening stage	0-20 cm	2.9 ± 0.3 c	19.3 ± 1.9 a	17.3 ± 5.6 ab	15.0 ± 2.1 ab	14.5 ± 2.1 ab	13.0 ± 1.0 b
	20-40 cm	2.5 ± 0.7 d	18.2 ± 3.5 b	23.3 ± 2.1 a	21.7 ± 4.4 ab	11.9 ± 1.7 c	11.4 ± 2.4 c
	40-60 cm	2.0 ± 0.6 d	24.6 ± 2.7 a	16.3 ± 3.2 b	14.6 ± 1.6 b	10.0 ± 0.7 c	10.5 ± 1.5 c
	60-80 cm	1.2 ± 0.4 d	23.2 ± 2.8 a	14.1 ± 2.2 b	15.5 ± 2.4 b	9.1 ± 0.4 c	9.2 ± 1.0 c
	80-100 cm	1.5 ± 0.3 d	20.3 ± 2.1 a	15.1 ± 2.2 b	14.5 ± 1.5 b	8.1 ± 1.8 c	7.3 ± 1.7 c

Note: Different letters in the same column signify significant difference at  $p < 0.05$ . CK represented no fertilization treatment, IF represented merely mineral N fertilization treatment, S25/ S50/ S75/ S100 delegated 25%/ 50%/ 75%/ 100% corn straw return + remaining N supplemented by mineral N

In the tassel emergency stage, NO<sub>3</sub><sup>-</sup>-N of the 0-20 cm for all straw application treatments were 12.4%, 22.6%, 27.4% and 35.8% lower than IF, respectively. The differences of the latter three treatments were significant at 0.05 levels, indicating an obvious decreasing trend with increasing straw application rate. Compared to IF, the mean reduction of the four straw application treatments was 5.6 mg/kg in 0-20 cm,

9.0 mg/kg in 20-40 cm, 8.0 mg/kg in 40-60 cm, 4.4 mg/kg in 60-80 cm and 7.8 mg/kg in 80-100 cm. The average NO<sub>3</sub><sup>-</sup>-N contents in 0-20 cm and 80-100 cm soil layer of all straw application treatments were 17.1 mg/kg and 5.8 mg/kg, respectively. It decreased by 11.3 mg/kg from the top layer to the lowest layer, which was larger than that of 9.1 mg/kg in IF. More straw application was added, lower NO<sub>3</sub><sup>-</sup>-N was obtained. For S100, it decreased by 8.1- 12.9 mg/kg in different soil layers, or 35.8%-80.0% compared with corresponding layers of IF, which decreased more than other straw application treatments.

In the fully ripening stage, NO<sub>3</sub><sup>-</sup>-N in all straw application treatments was still lower than IF. For IF, NO<sub>3</sub><sup>-</sup>-N distribution in soil profile showed a completely opposite characteristic to tassel emergency stage as 40-100 cm soil layers was 3.9 mg/kg higher than that in 0-40 cm, which indicated that more NO<sub>3</sub><sup>-</sup>-N migrated to deeper soil layers. But for all straw application treatments, it was still higher in the two top layers than that in 40-100 cm with an average content of 14.8 mg/kg to 12.0 mg/kg, which decreased by 4.0 mg/kg in 0-40 cm and 10.7 mg/kg in 40-100 mg/kg compared with the corresponding layers of IF. A larger decreasing occurred in deeper layers of straw application treatments indicated that straw combined with reduced mineral N fertilizer prevented nitrate nitrogen leaching in soil profile. As straw application increasing accompanied by mineral N fertilizer application decreasing, less NO<sub>3</sub><sup>-</sup>-N was left in soil profile. S100 had the lowest level with a decrease of 6.3-14.1 mg/kg, or 32.6%- 64.0% in different soil layers compared with IF.

#### ***Ammonium distribution in soil profile***

Ammonium distribution in soil profile is indicated in *Table 5*. NH<sub>4</sub><sup>+</sup>-N in all fertilization treatments was significantly higher than CK ( $p < 0.05$ ) and high level of straw application was significantly higher than IF.

**Table 5.** NH<sub>4</sub><sup>+</sup>-N content in soil profile in different fertilization treatments in tasseling and fully ripening stage (mg/kg)

	Profile	CK	IF	S25	S50	S75	S100
Tassel emergency stage	0-20 cm	3.2 ± 1.0 b	11.8 ± 1.6 a	11.3 ± 1.6 a	12.3 ± 1.2 a	12.5 ± 3.3 a	10.6 ± 2.7 a
	20-40 cm	3.8 ± 0.7 c	12.0 ± 1.3 a	12.8 ± 1.9 a	10.5 ± 2.4 ab	11.3 ± 1.8 ab	8.9 ± 0.2 b
	40-60 cm	3.6 ± 0.5 d	5.6 ± 0.6 c	5.8 ± 0.3 c	10 ± 1.7 ab	10.6 ± 1.2 a	8.8 ± 0.3 b
	60-80 cm	2.5 ± 0.7 c	5.8 ± 0.9 b	5.3 ± 0.6 b	9.7 ± 1.4 a	10.6 ± 1.2 a	6.8 ± 0.8 b
	80-100 cm	1.1 ± 0.5 c	3.2 ± 0.6 b	3.1 ± 0.5 b	4.5 ± 0.9 ab	5.3 ± 1.2 a	5.2 ± 0.8 a
Fully ripening stage	0-20 cm	2.3 ± 0.5 c	9.2 ± 1.0 b	12.6 ± 1.1 a	11.5 ± 2.6 ab	12.9 ± 1.4 a	13.4 ± 2.5 a
	20-40 cm	2.5 ± 0.5 c	8.5 ± 0.9 b	11.7 ± 0.9 a	11.3 ± 0.3 a	11.8 ± 0.3 a	10.8 ± 0.8 a
	40-60 cm	2.3 ± 0.4 d	3.4 ± 0.3 d	6.1 ± 0.7 c	8.8 ± 0.9 ab	8.6 ± 0.9 b	10.1 ± 0.9 a
	60-80 cm	1.5 ± 0.2 e	4.0 ± 0.4 d	4.5 ± 0.5 d	10.7 ± 1.0 b	14.0 ± 0.8 a	8.7 ± 0.6 c
	80-100 cm	0.9 ± 0.1 c	5.7 ± 0.7 b	5.6 ± 0.2 b	5.3 ± 0.7 b	7.4 ± 0.3 a	7.3 ± 0.8 a

Note: Different letters signified significant difference at  $p < 0.05$  among different treatments. CK represented no fertilization treatment, IF represented merely mineral N fertilization treatment, S25/S50/S75/S100 delegated 25%/50%/75%/100% corn straw return + remaining N supplemented by mineral N

In the tassel emergency stage, no significant difference was found between NH<sub>4</sub><sup>+</sup>-N content of IF and straw application treatments in the 0-20 cm and 20-40 cm soil layers ( $p > 0.05$ ). While it was obviously increased by 3.2 mg/kg in 40-60 cm, 2.3 mg/kg in



60-80 cm and 1.3 mg/kg in 80-100 cm. S75 had the highest  $\text{NH}_4^+\text{-N}$  content, which was 5.9% - 89.3% more than IF in different soil layers.

In the fully ripening stage,  $\text{NH}_4^+\text{-N}$  in each soil layer increased with straw application increasing and it was significantly higher ( $p < 0.05$ ) than IF and CK by an average of 3.5 mg/kg and 7.8 mg/kg, respectively. The same as tasseling stage,  $\text{NH}_4^+\text{-N}$  declined with soil depth, while straw application treatments could slow down this trend in 40-80 cm with an average of 8.9 mg/kg compared with 3.7 mg/kg of IF. Compared to tassel emergency stage,  $\text{NH}_4^+\text{-N}$  in CK and IF declined by 0.9 mg/kg and 1.5 mg/kg, respectively. Whereas straw application treatments enhanced  $\text{NH}_4^+\text{-N}$  content by an average of 0.9 mg/kg, which meant that straw combined with mineral N fertilizer relatively kept N in the form of  $\text{NH}_4^+\text{-N}$  long time and it may be related to the inhibition of nitrification.

## Discussion

### *Effect of straw application combined with reduced mineral N on corn grain yield*

In the present work, the corn yield of straw application treatments was significantly higher ( $p < 0.05$ ) than CK, which was consistent with other results (Uzoma et al., 2011; Liang et al., 2013). However, it did not show significantly higher than merely mineral fertilizer (IF) treatment in our research. There were two kinds of completely different view on the effect of applying organic matter on grain yield. Some results showed organic combined with mineral fertilizer improved crop yield greatly, such as Subehia et al. (2013), who confirmed that 50% N replaced by farmyard manure greatly increased rice and wheat yield than 100% chemical fertilizer treatment. While a number of previous studies had opposite results, which indicated that nitrogen application amount was the key factor affecting crop yield compared to fertilizer types. For example, Basso et al. (2005) and Biau et al. (2012) thought there was no significant difference in corn yield between treatments of manure, compost and mineral fertilizer in multi-year field experiment. Luo (2015) found that nitrogen improved corn yield by 53.5%- 130.7%, while organic fertilizer only increased by 8.8%- 22.1%. Zhou et al. (2013) deemed that low and high organic and mineral nitrogen ratio was adverse to yield and recommended the best ratio of 2:3 for improvement of Soda Alkali soil.

In our result, straw combined with mineral N fertilizer didn't significantly increase corn yield compared with IF. It partly was relative to the higher background of SOM in testing soil. New added straw in our study mineralized slowly in the fertilizing year and its contribution to increase SOM was relatively small on the high background. Oldfield (2019) found that crop yield increased significantly with the increase of SOM as it was below 2%. Zhang et al. (2016) carried out one field experiment on a typically low SOM soil, and also believed that the increase of SOC determined the increase of crop yield. Li et al. (2017b) suggested that replacing partial NPK fertilizers by manure could sustain high corn yield when SOC reached 41.96 Mg C/ha in the Northeast China Plain. If SOC was higher than this threshold, the effect would not be realized. Additionally, it would take at least decade to unfold this effect because it was a long time for microorganism to mineralize manure to release nutrients for crops to take up. Biau et al. (2012) found that the mineral N fertilizer had higher average grain yield and plant N uptake than pig slurry and attributed the result to agronomic management practices and the climate. Therefore, the effect of straw application on grain yield and plant N uptake was determined by multiple factors and it was a comprehensive result. In order to evaluate it correctly, the

response of corn crops to different forms of N fertilizer should be considered in the same farming practices and climate.

Furthermore, corn yield didn't keep in the increasing trend, but decreased when straw application increased to 100%. We attributed this phenomenon to its lower germination rate and rows per ear. Although some studies showed that organic matter enhanced the soil water content and was benefit of germination and crop growth (Li et al., 2020), the straw application amount and mode was extremely important factors determined its effect on plant growth (Wang et al., 2018b; Zhen et al., 2020). For example, Fan et al. (2005) found that 3.75 t/ha straw combined with mineral N and P increased soil water-holding capacity and improved water availability to plants to increase grain yield, in which the application straw amount was much lower than our experiment and did not influence corn germination rate. Liu et al. (2020) discovered that subsoiling with straw application was a promising strategy to improve wheat yield and water use efficiency for retaining soil water availability, in which subsoiling was done by a rotary cultivator in 40-45 cm soil depth. It was deeper than our study and kept the surface soil unchanged so that it had little effect on the surface evaporation of soil moisture, and however increased the water holding capacity of subsoil. Zhao et al. (2011) also pointed out that high quantities of decomposed cow dung and mineral fertilizers increased field moisture capacity by 11.25% and increased grain yield by 0.8%-9.4% than the single chemical fertilizers. The difference between our results was the types of organic matter, which affected soil structure and consequent water availability differently. Moreover, there was no artificial irrigation in our testing area which made the soil germinating condition even worse in a windy and less rainfall climate.

### ***Effect of straw application combined with reduced mineral N on N accumulation in corn plant***

In the present work, as long as the total nitrogen application rates was identical, no matter it was in inorganic/organic form, or combining, their nitrogen harvest index changed little, and was significantly higher than no fertilization treatment. However, this result was not consistent with some others which believed that different nitrogen forms and combining ratio influenced harvest index obviously (Tan et al., 2011). We attributed it to the high background level of SOM which decreased the effect of added straw, and it was also partly related to incomplete decomposition of straw in a short time.

In the whole growth period, fertilization treatments (both organic and inorganic) promoted nitrogen accumulation in plant, and they were significantly higher than CK because more N was supplied, which is in-line with previous reports (Berenguer et al., 2008). Abbasi and Almas (2012) reported that integrated use of organic and inorganic N sources increased corn growth and N uptake by plants compared to sole application of organic or chemical N fertilizer. Rees and Castle (2002) deemed that total uptake of N by plants in poultry manure was higher than those in ammonium sulphate.

In addition, S75 had the highest nitrogen use efficiency in our study which indicated that appropriately combined with straw and mineral N fertilizer could increase nitrogen use efficiency significantly. Dordas et al. (2008) and Martínez et al. (2017) pointed out that nitrogen use efficiency decreased with increased mineral fertilizer supply. However, our result was consistent with their conclusion except for S100, which was a little lower than other straw application treatments. We attributed it to the lower germination rate which affected grain yield, as well as to the higher straw application amount which consumed more mineral N for microbial growth so as to decrease the source of N for corn

absorbing. Zhi et al. (2020) conducted a  $^{15}\text{N}$  tracer experiments and deemed that nitrogen use efficiency was different regionally which caused more by soil properties than by climatic factors. In his study, nitrogen use efficiency in Northeast China was 47%, which was much higher than in North Central region of China (28%). In our study, the average nitrogen use efficiency of straw application treatments was 48.7% and the mineral N fertilizer treatment was 42.5%, which was greatly higher than the average of 38% in Chinese corn system (Zhi et al., 2020).

### ***Effect of straw application combined with reduced mineral N on $\text{NO}_3^-$ -N distribution in soil profile***

In all, S75 and S100 greatly declined  $\text{NO}_3^-$ -N in 0-100 cm soil profile compared with IF and S25, S50. More  $\text{NO}_3^-$ -N was kept in 0-40 cm in all straw application treatments, while a migrating to deeper soil was discovered in IF, which indicated that straw application combined with reduced mineral N fertilizer affected  $\text{NO}_3^-$ -N distribution in soil profile by two ways, one was to decrease its content and the other was to resist its downward migration to deeper soil layers.

Nevertheless, the results of studies about the effects of organic matter application on nitrate leaching found in literature were discording. Martínez et al. (2017) found that N remained in organic form when manure was applied and was less prone to losses than mineral N fertilizer. Berenguer et al. (2008) reported that pig slurry treatment had relatively lower level of residual  $\text{NO}_3^-$ -N than equivalent dose of mineral fertilizers and suggested that more N was immobilized as form of  $\text{NH}_4^+$ -N in the soil. Bai et al. (2015) also supported the view that beneficial reduction of nitrate leaching was elicited by organic fertilizers. However, some research indicated that manure increased the risk of nitrate leaching if it was applied in autumn-winter application or in soils with high soil organic matter (Chambers et al., 2000; Chalmers, 2001; Wang et al., 2002). We attributed these different opinions to drainage amounts, which was supported by Jabloun et al. (2015) who revealed that N leaching had a positive relationship with precipitation. In the area of abundant rainfall or artificial irrigation, especially in spring and autumn when the absorption capacity of plants to nitrogen was low, high drainage amount took more nitrogen to migrate down. But in the place with less rain, such as our testing position, more nitrogen fixed by microorganism or absorbed by soil aggregates and stayed in the upper soil which decreased the risk of N leaching with a positive impact on the environment.

### ***Effect of straw application combined with reduced mineral N on $\text{NH}_4^+$ -N distribution in soil profile***

Consistent with most of previous research, the application of N (both organic and mineral) in this work enhanced the soil ammonium content in 0-40 cm, which was higher than CK (Martínez et al., 2017). In tassel emergency stage, there was no significant difference about  $\text{NH}_4^+$ -N between IF treatment and other straw application treatments in the two top layers. But when corn was in mature period, all straw application treatments had higher  $\text{NH}_4^+$ -N than IF treatment, which could be relative to its sustained release during the whole growth period and the high adsorption capacity caused by straw return. Additionally, temperature at this time was enough high to activate mineralization of microorganisms. And in the later stage of growth, the ability of absorbing nitrogen by plants was weaken and biodegradable organic N was still decomposed by microorganism which resulted in a higher ammonium content than IF during fully ripening stage.  $\text{NH}_4^+$ -N

fixed in the interlayers of the clay minerals or absorbed by the surface of soil particles was not uptake by crop, and was not lost through volatilization, but was immobilized in soil and played an important role in the N budget.

## Conclusions

Straw return, as an important component of conservation tillage, has been widely adopted across the Northeast plain of China. Straw contains many nutrients which can slowly release for plant growth by microbial mineralization. Whether the released nutrients can replace partial chemical-fertilizers on the purpose of reducing fertilizer application in the fertilization year is still unclear in the intensive and continuous corn planting system in Northeast China.

Our results showed that although straw application did not lead to significantly increase in corn yield compared with merely mineral N fertilizer, 50% -75% straw application combined with reduced mineral N fertilizer on a total N application rate of 240 kg N/hm<sup>2</sup> was a relatively better fertilizing strategies from the perspective of both nitrogen use efficiency and residual nitrogen in soil in the fertilization year. This fertilization practice not only improved nitrogen use efficiency by 5.7-12.6% compared with merely mineral N fertilizer, but also reduced NO<sub>3</sub><sup>-</sup>-N amount and its migration to the lower soil layers to avoid contaminating groundwater. Ammonium content in straw return treatments was higher than merely inorganic fertilizer treatment in the fully ripening stage, which should be further researched to evaluate its role to the next planting in the future study.

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