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Evaluation of efficiency of controlled-release N fertiliser on tartary buckwheat production

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Abstract: To provide reference for scientific management of nitrogen (N) fertiliser on tartary buckwheat, the effects of the mixed application of controlled-release N fertiliser (a kind of thermoplastic polymer-coated urea types that are characterised by a semi-permeable membrane) and common urea was studied in the main tartary buckwheat production area in China. In 2018 and 2019, a two-year field experiment was conducted a randomised block design with five treatments: (1) no nitrogen fertilisation (CK); (2) 100% N from common urea (T1); (3) 15% N from controlled-released urea fertiliser (plastic coated) + 85% N from common urea (T2); (4) 30% N from controlled-released fertiliser + 70% N from urea (T3); (5) 45% N from controlled-released fertiliser + 55% N of urea (T4). The N fertilisation rate was 90 kg N/ha in all fertilisation treatments. The results showed: (1) the mixed application of controlled-release N fertiliser and common urea was conductive to enhance the yield, dry mass, N uptake and apparent N fertiliser efficiency (NFE), compared with a single application of common urea. In two seasons, NFE was 38.6% (T1), 48.6% (T2), 53.6% (T3) and 53% (T4), separately; (2) the mixed application of controlled-release N fertiliser and common urea could significantly increase the soil inorganic N content in the soil surface layer and decreased the leaching loss of N; (3) with the increasing ration of controlled-release N fertiliser, the tendency of increasing N content of crop uptake and soil residual and decreasing rate of N loss and N surplus was visible. Overall, considered the indicators of grain yield, input cost, N utilisation and N balance, the suitable N fertilisation mode for tartary buckwheat production is the mixed application of 30% controlled-release N fertiliser and 70% common urea when 90 kg N/ha is applied.

Keywords: minor crop; nutrition; crop-soil N balance; nitrogen fertiliser type

Tartary buckwheat (*Fagopyrum tataricum* L. Gaertn) is one kind of crop that has rich nutrition and healthy function. It consists of not only abundant protein, dietary fiber, vitamins, fat but also active constituents such as bioflavonoids that do not exist in other gramineous grain crops (Piao and Li 2001). The pharmacodynamic study of animals showed that these active constituents had the function of reducing blood glucose and blood fat and enhancing immune-modulating activity. Otherwise, its high rutin content has the function of reducing cholesterol and preventing cardiovascular and cerebrovascular diseases (Guo et al. 2012). Nowadays, with the widespread of lifestyle-related diseases such as hyperglycemia, hyperlipidemia and hypertension, the enhanced healthy consciousness of people leads to the high demand of tartary buckwheat products. Therefore, tartary buckwheat planting has a sig-

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nificant meaning for the promotion of functional agriculture in China.

Among all nutrient elements, nitrogen is the most sensitive element that affects the growth and yield of tartary buckwheat and has a strong relationship with the uptake of phosphorous and potassium. Tartary buckwheat has a N demand of 3–4 kg for 100 kg grains (Zhao et al. 2016). Nitrogen fertiliser promoted the yield and economical profit on a certain distance but lead to the deteriorated nutritional quality and production environment (Liu et al. 2013). At present, there is little information describing the changes of soil nitrogen for tartary buckwheat and the relationship of nitrogen fertiliser input, yield, and the situation of soil nitrogen.

The controlled-release N fertiliser, with the capacity to delay the availability of N for plant uptake, can meet the N demand of crop during the growth period by single basal application, which is beneficial for promoting the crop growth, reducing N loss, and enhancing yield and N use efficiency (Azeem et al. 2014). However, N release patterns, rates, and duration are strongly dependent on variable soil properties, in particular, biological activity and external conditions such as moisture content and temperature; thus, their effects on agriculture cannot be predictable and consistent (Aarnio and Martikainen 1995, Shaviv 2001). Furthermore, controlled-release N fertiliser is much more expensive than common urea (Watson 2013). Therefore, the technique of mixed controlled-release N fertiliser and common urea, which adjusts the application of slow-released N and readily soluble N, can meet the N demand of crop on different growth stages as well as reduce cost and environmental risk (Yang et al. 2005, Farmaha and Sims 2013). In Northeast China, the appropriate mixed ratio of controlled-release N fertiliser for spring maize production is around 45% when 185 kg N/ha is applied (Wang et al. 2016). In Southwest China, the application of 40% of CRF (controlled-release fertiliser) could improve soil N supply and enhance soil urease and protease activities; simultaneously, the effectiveness of N was promoted during the later growth stages of wheat and rice (Zhang et al. 2017). For the winter wheat-summer maize rotation system in the North China Plain, it was more conductive to enhance the total yield and N use efficiency when the ratio of controlled-release N fertiliser was 40% or above (Guo et al. 2017). The former research about the fertilisation techniques of mixed application of controlled-release N fertilisation was focused mainly on the yield, quality, and N uptake of the crop, but concerned less on soil N situation, especially the compensation function and environmental effects of the residual N. This research studied the effects of the application of different ratios of controlled-release fertiliser and urea on the yield, dry mass accumulation, N uptake and soil-crop N balance of tartary buckwheat in two seasons (2018 and 2019). The appropriate ratio of controlled-release N fertiliser would be confirmed by a comprehensive consideration of yield, N uptake and N balance, which would provide a reference for scientific management of N nutrition on the crop.

MATERIAL AND METHODS

Introduction of the experimental field. The experiment was conducted during the 2018 and 2019 seasons at Dongyang Experimental Station of Shanxi Academy of Agriculture Science, in Northern China (112°45'E, 37°40'N). The study area features a subtropical monsoon climate with an annual temperature of 9.7 °C, annual precipitation of 440.7 mm (75% of which falls from June to September), average annual sunshine duration of 2 662 h, and a non-frost period of 158 days. Soil from the field is classified as Calcisol, which is frequently soil type in Northern China. The chemical properties of the 0–20 cm soil layer before trial were 9.3 g/kg organic carbon, 98.6 mg/kg available nitrogen, 5.6 mg P/kg (Mehlich-3 method) (Monrawee et al. 2018), 115.3 mg K/kg (Mehlich-3 method) and pH 8.3 (in 0.01 mol/L $CaCl_2$ solution). The monthly average temperature and precipitation during the experimental period are as followed (Figure 1).

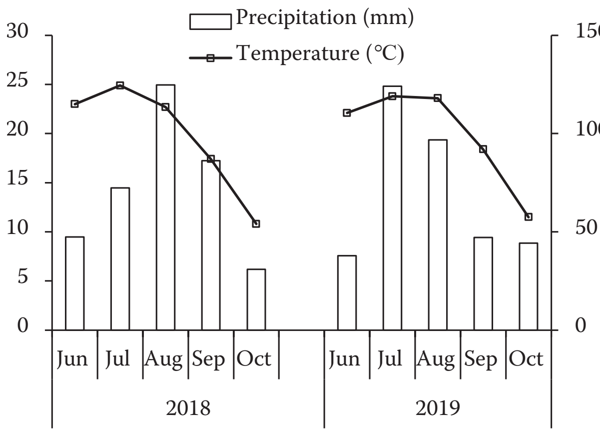

Figure 1. Monthly average temperature and precipitation during the experimental period

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Experimental designs. This study was conducted at 15 plots in a randomised-block design with three replicates comparing five treatments. The plot dimensions were 5 m width and 8 m length. Treatments were: (1) no N fertiliser (CK); (2) 100% N from urea (T1); (3) 15% N from controlled-released fertiliser + 85% N from urea (T2); (4) 30% N from controlled-released fertiliser + 70% N from urea (T3); (5) 45% N from controlled-released fertiliser + 55% N from urea (T4). The total N in treatments T1, T2, T3 and T4, 90 kg N/ha was applied. The controlled-released N fertiliser, with N content of 44.5%, release curve of "S" (slow-fast-slow) and release longevity of 60 days, was one kind of thermoplastic polymer-coated urea types that are characterised by a semi-permeable resin membrane that enables water to enter the granule and to dissolve the N inside, which was obtained from the Sino-Arab Fertiliser Co (Qinhuangdao, Hebei, China). The conventional urea product contained 46% N. The input of phosphate and potash fertilisers were the same, with 52.8 kg P/ha (superphosphate) and 43.6 kg K/ha (potassium sulfate), separately. All the fertilisers were applied before sowing. The field management was the same as the conventional practice of farmers except for the fertilisation methods.

The planting density of buckwheat was 7.5 × 10^5 plants/ha in both 2 seasons. In 2018, Jinku No. 6, as the application breeder, was sown on June 20th and harvested on October 3rd, which has a growth period of 106 days; in 2019, Jinku No. 6, as the application breeder, was sown on June 15th and harvested on October 4th, which has a growth period of 111 days. Manual irrigation was not applied in any field during the two-year field experiment. Buckwheat was cultivated on the same experimental plots in 2018 and 2019.

Measuring items and calculation formula. In 2018, soil samples of 0–20 cm soil layer of the field were taken, and basic chemical properties of soil were measured by conventional method (Gao et al. 2009). Before sowing and after harvesting in each year, the soil samples (0–20, 20–40 and 40–60 cm soil layers) of each plot (each has five duplications) were obtained by the soil-drilling method and were taken to the lab with icebox. After sieving by 5 mesh screen, the fresh soil samples were extracted by 0.01 mol/L $CaCl_2$ solution (soil solution ratio was 1:10) with mechanical shaking extractor for 10 min; then the suspension was filtrated. NO_3^--N and NH_4^+-N were measured by SFA Segmented Flow Analysis (Alliance Corp., Paris, France). Soil water content was 15.0% on 0–20 cm layer.

The yield of tartary buckwheat was measured in each plot after harvest. Fifteen representative plants were chosen from each plot and were smashed and weighted before separation and desiccation of straws and grains. N concentration of grain and straw were measured using the Kjeldahl method.

Methods of calculating N-relevant parameters were given as Ju et al. (2002):

N mineralisation content during the growth period (kg/ha) = N content of crop uptake (CK) + soil residual inorganic N content (CK) – soil initial inorganic N content (CK).

Apparent N loss content during the growth period (kg/ha) = (N fertiliser input + soil original inorganic N content + N mineralisation content during the growth period) – (N content of crop uptake + soil residual inorganic N content after harvest).

N surplus content (kg/ha) = apparent N loss content + soil residual inorganic N content after harvest.

Apparent N-fertiliser efficiency (%) (NFE) = (N uptake of the crop in fertiliser treatment – N uptake of the crop in control)/(N fertiliser application) × 100.

Note: (1) N uptake of the crop was measured and analysed by the total above-ground biomass (except root); (2) soil inorganic N content was measured in 0–60 cm soil layer; (3) the calculation of apparent N loss is different from the measured values of N loss by ^{15}N-labelled method, it included all kinds of the fate of N fertiliser (soil biological fixation, leaching, ammonia volatilisation, etc.).

Statistical analysis. Experimental data were calculated with Excel 2010 software (Microsoft Corp., Seattle, USA). Statistical analysis of the data was conducted with SAS 8.1 software (SAS Institute Inc., North Carolina, USA). All treatments were compared by ANOVA performed with the *LSD* (least significant difference) method with 2 fixed factors (year and fertilisation) and their interactions. All statements of significance were based on a probability of 0.05.

RESULTS

Grain yield and N uptake. The experiment year and treatment affected the yield of tartary buckwheat significantly, and there were significant interaction effects between years and treatments (Table 1). In 2018, the yield of all the treatments was relatively lower than that in 2019, but the results of yields in 2 years showed the same tendency. The applica-

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Table 1. Grain yield and nitrogen (N) uptake of tatary buckwheat

Year	Fertiliser treatment	Grain yield (t/ha)	Increased rate (%)	Dry mass (t/ha)	N uptake (kg/ha)	Apparent N-fertiliser efficiency (%)
2018	CK	1.68^c	–	3.59^c	49.2^c	–
	T1	2.19^b	30.4^b	5.01^b	82.7^b	37.2^c
	T2	2.39^a	42.5^a	5.39^a	89.0^{ab}	44.2^b
	T3	2.47^a	47.0^a	5.50^a	96.2^a	52.1^a
	T4	2.47^a	47.0^a	5.54^a	95.4^a	51.2^a
2019	CK	1.57^c	–	3.47^c	47.2^c	–
	T1	2.21^b	41.1^b	5.03^b	83.2^b	40.0^b
	T2	2.51^a	60.1^a	5.55^a	94.9^a	53.0^b
	T3	2.55^a	62.7^a	5.59^a	96.7^a	55.0^a
	T4	2.49^a	58.5^a	5.54^a	96.4^a	54.7^a
ANOVA						
Year (Y)		**	**	**	**	**
Fertiliser (F)		**	*	**	**	*
Y × F		**	ns	**	**	*

Different letters in each column indicate significant differences between different fertiliser applications (P < 0.05); *P < 0.05; **P < 0.01; CK – no N fertiliser; T1 – 100% N from urea; T2 – 15% N from controlled-released fertiliser + 85% N from urea; T3 – 30% N from controlled-released fertiliser + 70% N from urea; T4 – 45% N from controlled-released fertiliser + 55% N from urea

tion of nitrogen fertiliser could increase the yield in 2 years, compared with CK treatment. The treatments of mixed application of controlled-release N fertiliser and urea increased yield significantly compared with the T1 treatment, and no differences were found between the various mixed ratios. Accordingly, mixed application of controlled-release N fertiliser and urea is more conductive to improve grain yield than the single basal application of urea. The average data in 2 years showed, T3 treatment achieved the highest grain yield with 2.51 t/ha, which was 14.1% higher than that of T1 treatment.

The dry mass and N uptake of tartary buckwheat showed significant differences among different years and treatments, and significant interaction effects were found between years and treatments (Table 1). The differences of dry mass among different fertiliser treatments were nearly the same with the result of grain yield. The two-year data showed that the treatment of T3 achieved the highest dry mass with 5.55 t/ha, which was 10.5% higher than that of the T1 treatment. In the two-year experiment, compared with CK treatment, the application of fertiliser could increase the N uptake significantly. The N uptake increased with the growing ratio of controlled-released N fertiliser, and it showed no significant effect when the ratio reached 30%. Therefore, moderate mixed application of controlled-release N fertiliser and common urea is beneficial for the dry mass accumulation and N uptake of tartary buckwheat.

Both experimental year and fertiliser treatment significantly affected the N-fertiliser efficiency. The apparent N-fertiliser efficiency (NFE) in 2019 was relatively higher than that of 2018. Compared with the T1 treatment, the treatments of mixed application of controlled-release N and urea increased NFE significantly with the increase ratio of controlled-release N fertiliser. The NFE was highest when the mixed ratio was 30% in 2019, while no significant differences were found among all the treatments of mixed application of controlled-release N fertiliser. For the two seasons, NFE (average) increased from 38.6% (T1) to 53.6% (T3), 53.0% (T4), and 48.6% (T2).

Soil inorganic N. Prior to sowing in 2018, soil inorganic N content decreased with the deepening of soil layers. The inorganic N contents of 0–20, 20–40 and 40–60 cm soil layers were 5.7, 3.1 and 2.6 mg/kg, separately (Figure 2A). After harvesting in 2018, the soil inorganic N content of nearly all nitrogen fertiliser treatments was lower than that prior to sowing, except 0–20 cm soil layers of T3 and T4 treatment and 40–60 cm soil layer of T1 treatment (Figure 2B).

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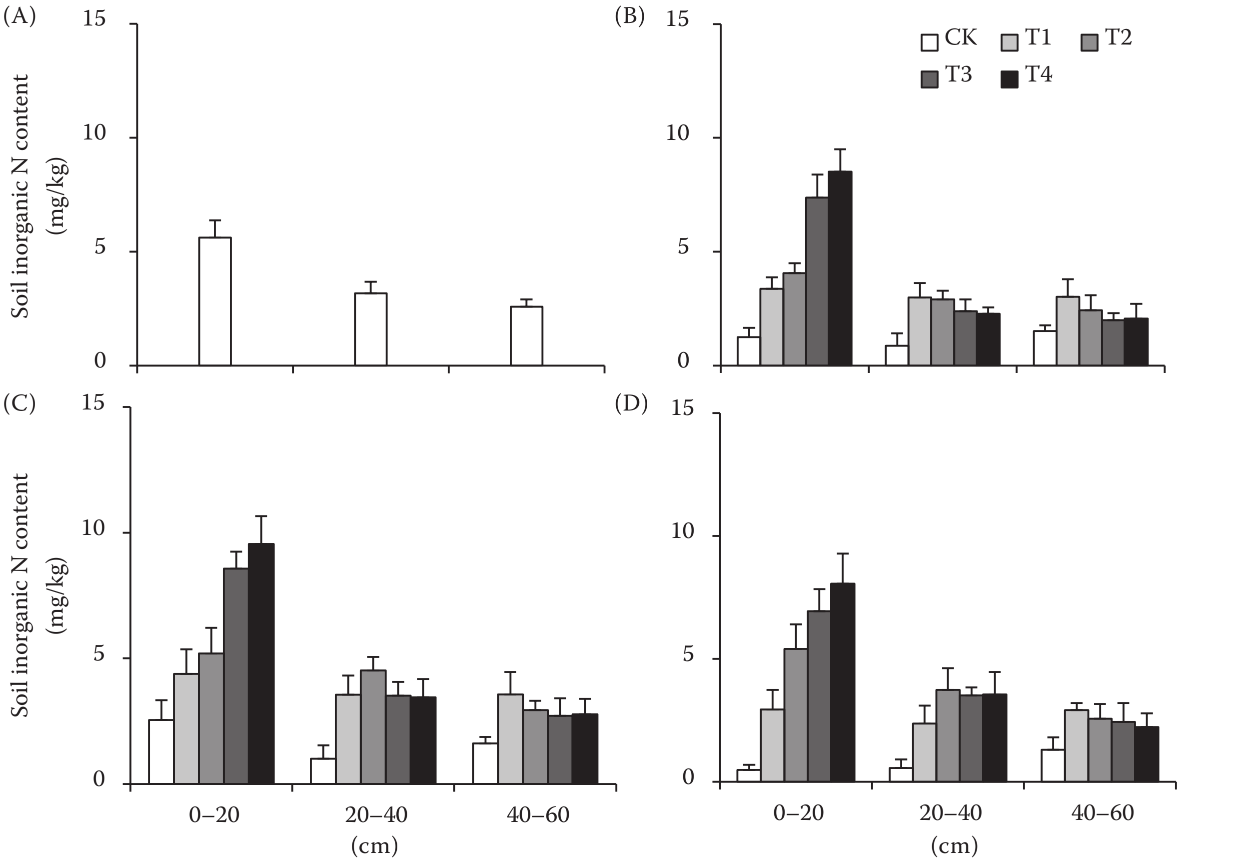

Figure 2. Soil inorganic nitrogen (N) content during the tartary buckwheat cropping seasons. (A) Prior to sowing in 2018; (B) after harvesting in 2018; (C) prior to sowing in 2019, and (D) after harvesting in 2019. CK – no N fertiliser; T1 – 100% N from urea; T2 – 15% N from controlled-released fertiliser + 85% N from urea; T3 – 30% N from controlled-released fertiliser + 70% N from urea; T4 – 45% N from controlled-released fertiliser + 55% N from urea

Compared with the treatment of N fertiliser input, the inorganic N content in 0–20, 20–40 and 40–60 cm soil layers of CK treatment decreased significantly to 2.5, 1.7 and 3.0 mg/kg. With the increasing ratio of controlled-release N fertiliser, the inorganic N content of 0–20 cm soil layer grew consistently, and T3 and T4 treatment were significantly higher than T1 and T2 treatment. The inorganic N content in relative deeper soil layers (20–40 cm and 40–60 cm) decreased with the higher ratio of mixed controlled-release N fertiliser, but no significant differences were found between different mixed ratios.

The inorganic N content in all soil layers prior to sowing in 2019 was relatively higher than that after harvesting in 2018, while no significant differences were found among different treatments (Figure 2C). After harvesting in 2019, except for the 0–20 cm soil layer of T1 treatment and 20–40 cm soil layer of T4 treatment, the inorganic N content of all the treatments was lower than that prior to sowing (Figure 2D). In 0–20 cm and 20–40 cm soil layers, the inorganic N contents of T1 treatment were significantly lower than that of all the mixed controlled-release N fertiliser treatments. The inorganic N content in the 0–20 cm soil layer increased with the growing ratio of controlled-release N fertiliser. In the 40–60 cm soil layer, no significant differences were found among different N fertiliser treatments.

Table 2 showed that the amount of inorganic N in the soil of all N fertiliser treatments decreased after harvesting compared with that prior to sowing (except T4 treatment in 2018). Compared with CK treatment, the inorganic N content of N fertiliser treatments after harvesting in two years increased significantly, which also increased with the ratio of controlled-release N fertiliser. The inorganic N content of T4 treatment was highest of all the treatments, with 102.8 kg/ha in 2018. The inorganic N contents of mixed application of controlled-release N fertiliser and common urea were significantly

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Table 2. Soil inorganic nitrogen (N) accumulation and mineralisation (0–60 cm soil layer)

Treatment	Inorganic N (kg N/ha)				N mineralisation (kg N/ha)		
	prior to sowing in 2018	after harvesting in 2018	prior to sowing in 2019	after harvesting in 2019	growing season in 2018	growing season in 2019	season between 2018 and 2019
CK	95.5	29.0^{c}	41.4^{c}	18.1^{c}	16.7	35.9	5.5^{b}
T1	95.5	74.9^{b}	92.0^{b}	63.3^{b}	16.7	35.9	6.7^{b}
T2	95.5	75.1^{b}	101.2^{b}	90.0^{a}	16.7	35.9	10.1^{a}
T3	95.5	94.0^{a}	118.4^{a}	99.3^{a}	16.7	35.9	10.3^{a}
T4	95.5	102.8^{a}	126.2^{a}	106.5^{a}	16.7	35.9	9.7^{a}

Different letters in each column indicate significant differences between different fertiliser applications ($P < 0.05$). CK – no N fertiliser; T1 – 100% N from urea; T2 – 15% N from controlled-released fertiliser + 85% N from urea; T3 – 30% N from controlled-released fertiliser + 70% N from urea; T4 – 45% N from controlled-released fertiliser + 55% N from urea

higher than that of T1 treatment. Compared with the T1 treatment, the application of mixed controlled-release N fertiliser and urea increased the average soil inorganic N in two years by 9.7–25.7%.

The N mineralisation under buckwheat consists of two parts: N mineralisation during the growth period and between the two growth periods of buckwheat (Table 2). The N mineralisation during the growth period in 2018 and 2019 were 16.7 and 35.9 kg/ha, separately. The N mineralisation of all treatments ranged from 5.5 to 10.3 kg/ha (the average content was 8.5 kg/ha). The N mineralisation content increased with the increasing mixed ratio. The results showed that mixed application of controlled-release N and common urea was beneficial to maintain a relatively higher N level in soil and promote the N mineralisation in wintering period.

N balance in the crop-soil system. Through the analysis of N balance in the crop-soil system during 2018–2019 cropping seasons (Table 3), the application of N fertiliser was the main mode of N input, accounting for 64.2% of total N input for N fertiliser treatments, while soil original N content and N mineralisation accounted for 17.0% and 18.8%, separately. Crop uptake was the main mode of N output, accounting for 71.6% of total N output averagely (ranging from 59.2% to 96.1%). With the increasing ratio of mixed controlled-release N fertiliser, the soil residual inorganic N increased, and the apparent N loss decreased so that the N surplus showed the tendency of decreasing.

In the 2018 season and 2019 season, the N surplus of treatments of mixed controlled-release N fertiliser was all lower than that of T1 treatment (except T4 treatment in 2019), but the tendency of N surplus in two seasons was different (Table 3), largely due to the differences of apparent N loss. T3 treatment decreased N loss significantly in 2019, and N loss of mixed application of controlled-release N fertiliser treatments was lower than that of T1 treatment. By comparing the soil balance in two seasons, both N mineralisation contents and crop N uptake contents showed the tendency of increasing in 2019. It was probably that the precipitation was too much during the sowing date and drought occurred during the seedling stage, limiting the emergency and growth of the seedling as well as the development and nutritious uptake for plants on the late stage in 2018. The results showed that mixed application of controlled-release N and common urea could diminish apparent N loss and N surplus, but the tendency might be different due to the changes of climate and crop growth conditions.

DISCUSSIONS

Yield and N use. In this study, the mixed application of controlled-release N fertiliser and common urea could increase the dry mass accumulation and N uptake, realising the simultaneously enhancement of grain yield and the apparent N fertiliser efficiency as well as the decrease of N loss. The analysis showed that the yield and dry mass of tartary buckwheat showed no significant differences among different ratios of controlled-release N fertiliser. It could increase the crop uptake N and soil inorganic N and decrease the N loss when the mixed ratio reached 15%. However, the mixed ratio should reach 30% by comprehensive analysis of soil-crop system N balance and N loss. Therefore, the appropriate mixed

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Table 3. Nitrogen (N) balance in the crop-soil system during 2018–2019 cropping seasons (kg/ha)

Item		CK	T1	T2	T3	T4
First season in 2018						
N input	N fertiliser rate	0	90	90	90	90
	soil original inorganic N	47.7	47.7	47.7	47.7	47.7
	N mineralisation	16.7	16.7	16.7	16.7	16.7
	total input	64.4	154.4	154.4	154.4	154.4
N output	crop uptake	49.2	82.7	89.0	96.2	95.4
	soil residual inorganic N	15.2	39.3	39.4	49.4	53.9
	apparent N loss	0.0	32.4	25.9	8.9	5.1
	N surplus	15.2	71.7	65.4	58.2	59.0
Second season in 2019						
N input	N fertiliser rate	0	90	90	90	90
	soil original inorganic N	20.7	46.0	50.6	59.2	63.1
	N mineralisation	35.9	35.9	35.9	35.9	35.9
	total input	56.6	171.9	176.5	185.1	189.0
N output	crop uptake	47.2	83.2	94.9	96.7	96.4
	soil residual inorganic N	9.4	32.9	46.8	51.6	55.3
	apparent N loss	0.0	55.9	34.8	36.9	37.3
	N surplus	9.4	88.8	81.6	88.4	92.6
Two seasons in 2018 and 2019						
N input	N fertiliser rate	0	180	180	180	180
	soil original inorganic N	47.7	47.7	47.7	47.7	47.7
	N mineralisation	52.6	52.6	52.6	52.6	52.6
	total input	100.3	280.3	280.3	280.3	280.3
N output	crop uptake	96.4	165.9	183.9	192.9	191.8
	soil residual inorganic N	9.4	32.9	46.8	51.6	55.3
	apparent N loss	–5.5	81.6	49.6	35.9	33.2
	N surplus	3.9	114.4	96.4	87.4	88.5

CK – no N fertiliser; T1 – 100% N from urea; T2 – 15% N from controlled-released fertiliser + 85% N from urea; T3 – 30% N from controlled-released fertiliser + 70% N from urea; T4 – 45% N from controlled-released fertiliser + 55% N from urea

ratio of controlled-release N fertiliser for tartary buckwheat production in this study is around 30% when 90 kg N/ha is applied. The results on tartary buckwheat were consistent with other crops overall, but the appropriate mixed ratio of controlled-release N fertiliser for buckwheat was relatively lower than other crops (Si et al. 2013, Yi et al. 2013, Zhang et al. 2017). On the one hand, the climate and soil conditions in different regions are relatively different; on the other hand, because of the differences of growth period of different crops, the crop with relatively longer growth period demanded a higher ratio of controlled-release N fertiliser to meet the demand of N for the middle and late growth stages.

Crop-soil system N balance. For the crop-soil system, the fate of N fertiliser mainly includes three aspects: (1) crop uptake; (2) organic and inorganic N residual in soil profile; (3) N loss by ammonia volatilisation, mineralisation – denitrification, leaching and runoff (Ju and Christie 2011). The redundant N loss can not only affect the plant growth and decrease the apparent N fertiliser efficiency but also lead to serious environmental risk (Nosengo 2003, Conley et al. 2009). Therefore, indicators such as yield, economical profit and quality, N fate and N balance of the crop-soil system should be considered when the technique of fertilisation is evaluated. At present, the study of the fertilisation technique for

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tartary buckwheat main focused on yield and N uptake and discussed less on the N transformation and N balance in the soil. The research showed that the mixed application of controlled-release N fertiliser could significantly increase the nitrate and exchangeable ammonium contents in the topsoil and decrease the N leaching into the deep soil. The high level of inorganic N residual is an important cause for N loss; therefore, it should be limited to a certain range when crop uptake and environmentally friendly are taken into consideration (Ju et al. 2009). The inorganic N residual should be less than 90 kg/ha by some European countries (Jemison and Fox 1994). In this study, the inorganic N residual of mixed application of controlled-release N fertiliser was relatively higher than that of a single application of urea but remained at the appropriate level, so it would not lead to serious N loss after harvesting; in contrary, it increased the N mineralisation on the gap period of two seasons. It was estimated that the N loss of fertiliser was about 45% for rainfed agriculture in China (Ju et al. 2009). Normally, the growth period of tartary buckwheat is on rainy season, so the input of available N fertiliser may lead to leaching and runoff of N. In this study, the mixed application of controlled-release N fertiliser could decrease the apparent N surplus significantly compared with a single application of common urea; the apparent N surplus was lowest when the ratio of controlled-release N fertiliser was 30%, which was 23.6% lower than that of common urea treatment. Therefore, from the point of soil-crop N balance, the mixed application of controlled-release N fertiliser could decrease the apparent N loss and N surplus and increase the N uptake of crop and N use efficiency.

Influence factors of controlled-release N fertiliser. The effect of mixed application of controlled-release N fertiliser is affected by many factors (such as nutrient demand characters of the crop, climate condition, soil condition and so on), of which climate factor have the strongest influence due to temperature and humidity affecting the nutrient-release character, nutrient transformation, and activation process in the soil (Huett and Gogel 2000, Yang et al. 2010). Normally, a higher temperature can accelerate the nutrient release of N fertiliser; also, the higher soil water content can promote the release. The growth environment can affect the effect of mixed controlled-release N fertiliser significantly. Under the condition of dry and cold, it will inhibit the N release of controlled-released fertiliser and reduce the N uptake of the crop (Farmaha and Sims 2013). In this study, the controlled-release N fertiliser we used was one kind of thermoplastic polymer-coated urea types that is characterised by a semi-permeable membrane, which was significantly affected by soil moisture. The climate conditions in the 2018 season and 2019 season were quite different; however, the mixed application of controlled-release N fertiliser and urea increased grain yield significantly and reduce N leaching in two seasons. Hence, research should be focused on the effects of climate and environmental conditions on the N release and N dynamics of mixed application of controlled-release N fertiliser. The appropriate mixed ratio and types of controlled-release fertiliser under several climate conditions should be explored, which can further optimise the fertilisation technique to realise the synchronisation of time and space for N uptake of the crop.

Soil enzymes participate in nitrogen cycling processes and play important roles in the mineralisation and immobilisations as well in denitrification processes. Urease and nitrification inhibitors are compounds for increasing the apparent N fertiliser use efficiency of urea or ammonium fertilisers. Urease inhibitors mainly reduce the ammonia volatilisation loss by reducing the urease activity, while nitrification inhibitors inhibit the nitrification of ammonium, which can reduce nitrate leaching or denitrification. Studies have shown that urease inhibitors and nitrification inhibitors can reduce the accumulation and loss of soil nitrogen and improve fertiliser utilisation efficiency (Zaman et al. 2009, Cui et al. 2013). Therefore, based on the study of control-released urea, it is of great significance to explore the effects of urease and nitrification inhibitors on soil enzyme and nitrogen transformation to optimise nitrogen nutrient management and sustainable development of tartary buckwheat farmland.

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