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Slow-release nitrogen fertiliser suitable for one-time fertilisation of spring maize in Northeast China

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Abstract: Slow-release nitrogen fertiliser can potentially increase crop production and improve fertiliser nitrogen use efficiency. However, it is unclear that are suitable for different regions and crops in the northeast of China. Therefore, according to different soil and climate characteristics, we investigated the synchronised relationships between nitrogen slow release fertiliser and nitrogen maize requirements. Experiments were conducted at Shenyang Agricultural University, Liaoning province, Northeast China, from 2016 to 2017. Stabilised fertiliser treatments increased grain yield, nitrogen use efficiency and nitrogen accumulation at each maize growth stage. Grain yield increased by 2.32% and 11.33% (2016), and 1.55% and 7.87% (2017), respectively, when compared with the urea CK1 (233 kg N/ha) and CK2 (210 kg N/ha) treatments. Additionally, during the growth period of the stabilised fertiliser treatment, the stability of the synchronisation relationship between nitrogen absorption and absorption of spring maize was significantly higher than other treatments, and the effect was the best. Therefore, we conclude that the stabilised fertiliser is the most suitable option for promotion and application in spring maize in Northeast China.

Keywords: *Zea mays* L.; macronutrient; leaching; soil inorganic nitrogen; spatial-temporal variation

Northeast China is the major corn-producing area in China and plays an important role in the national food security production (Zheng et al. 2016). Nitrogen (N) is the main component of proteins, nucleic acids, and chlorophyll in plants, as well as a component of various enzymes in plants, and nitrogen nutrition directly affects crop yield and quality (Raja 2001, Zhao et al. 2003). Slow/controlled-release nitrogen fertiliser is a highly efficient and environmentally friendly way for slow or controlled release of nutrients in the soil, often with release time and intensity that are basically synchronised with crop nutrient demands (Shaviv and Mikkelsen 1993, Zheng et al. 2017). Therefore, it can potentially increase crop production, improve fertiliser nitrogen use efficiency (NUE), reduce fertiliser nutrient loss, leaching and denitrification in the soil, and significantly reduce apparent nitrogen loss in the 0–90 cm soil layer during maturity (Yun et al. 2010, Fang et al. 2013, Zheng et al. 2017, Tian et al. 2018). Additionally, with socio-economic changes like the rest of the country, the northeast region has a labor shortage for agricultural production. Therefore, slow/controlled-release nitrogen could have broad application prospects for spring

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maize production in Northeast China. However, in regional farmland ecosystems, due to differences in production technology, different types of slow/controlled-release nitrogen fertilisers also have different nutrient release rates under different climate, soil environments, crop types and cultivation models (Wang et al. 2013, Liu et al. 2019). Some studies have demonstrated that under different soil types and climatic conditions, the application effects of controlled-release nitrogen fertilisers are not the same (Geng et al. 2015, 2016, Zheng et al. 2016). There are many types of slow/controlled-release fertilisers on the local market, with different nutrient distribution ratios (Wu et al. 2018), making it difficult to adjust measures to local conditions for optimal efficiency. Furthermore, some manufacturers even avoid the shortcomings of slow controlled-release nitrogen fertiliser by exaggerating its effects (Feng et al. 2019), making it difficult for farmers to make the right choice. Therefore, according to regional climate and soil environment differences, there is a very urgent need to study and screen suitable controlled-release fertiliser types for different production areas to achieve simplified, sustainable spring maize production.

We screened four types of slow/controlled-release fertilisers, which are representative and widely used in agricultural production. With matching, nutrient release characteristics and nitrogen demand of spring corn under different slow/controlled-release fertiliser nitrogen reduction application conditions were carried out in central and southern Liaoning. Our primary objectives are to screen the types of controlled-release nitrogen fertiliser suitable for local soil and climatic conditions, provide a scientific basis for the economical and efficient application of the fertiliser, and simplify spring maize cultivation techniques in the region.

MATERIAL AND METHODS

Site description and experimental materials. Field experiments were conducted during two single croppings, maize growing seasons (May–September 2016, 2017) using the "nitrogen-sensitive" maize cv. Dongdan 6531 at the New Fertiliser Experiment Station, Shenyang Agricultural University, Liaoning province, China (40°48'N, 123°33'E). The test soil was classified as Typic-Hapli-Udic Argosols according to the Chinese Soil Taxonomy (CRGCST 2001) and as Typic Hapludalf according to USDA Soil Taxonomy (Soil Survey Staff 1999). The soil texture was sandy loam (Miller and Miller 1987). The initial statuses of 0–20 cm soil layer at the experimental site are shown in Table 1. This region has a typically temperate and monsoon climate, which is an average annual rainfall of 574~684 mm, an average annual temperature of 7.0~8.1 °C, and a frost-free period of 148–180 days.

The four typical slow/controlled-release nitrogen fertilisers used were: stabilised urea with a nitrification urease and inhibitor (F1, 26% N, added urease/nitration inhibitor to conventional compound fertilisers), urea-formaldehyde (F2, 26% N, a certain proportion of methyl urea polymers with different chain lengths are added to the compound fertiliser. Cold water-insoluble nitrogen accounts for 67.5% of the total nitrogen, and the activity index is 52%), biochar-based compound fertiliser (F3, 24% N, biomass charcoal is the main encapsulating material for compound fertiliser) and sulfur-coated urea (F4, 37% N, using sulfur as the main encapsulating material to cover granular urea, with a longevity of 90 days). Additionally, three conventional fertilisers were used: urea (46% N) as nitrogen, superphosphate (6.1% P) as phosphorus, and potassium sulfate (41.5% K) as potassium fertiliser, respectively.

Experimental design and field management. We established seven nitrogen fertiliser treatments in a randomised block design with three replicates: (1) no nitrogen fertiliser (CK); (2) common application of urea (CK1); (3) 90% conventional urea control treatment (CK2); (4) urea with a nitrification urease and inhibitor (F1); (5) urea-formaldehyde (F2); (6) compound fertiliser coated with biochar (F3), and (7) sulfur-coated urea (F4). CK1 was a fertiliser mixture with an N application rate of 233 kg/ha, and CK2 was

Table 1. The soil properties at the experimental site at the beginning of the experiment in 2 maize growth seasons

Growth season	pH_{H_2O}	Soil organic carbon	Total N	Nitrate N	Ammonium N	Olsen-P	Exchangeable K
		(g/kg)		(mg/kg)			
2016	5.14	8.47	0.83	6.97	6.17	7.60	89.80
2017	5.30	8.54	0.84	18.30	3.00	8.50	90.25

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a mixture with a nitrogen application rate of 210 kg/ha. Slow-release fertiliser nitrogen dosage was the same as CK2. The conventional nitrogen application rate in the test area was chosen as the recommended fertiliser application rate of the soil testing and fertilisation project in Liaoning province (Feng et al. 2019). Phosphate and potassium fertilisers in all treatments were applied to each crop in a single basal application of 97.5 kg P/ha and 101.5 kg K/ha, respectively. All fertilisers were used as the only basic application was done as well for conventional fertilisers and applied to the soil 8–10 cm below the seed row side by ridge application at one time before sowing. Maize seeds were sown in 7 rows per plot with 60 cm between rows for a density of 67 500 plants/ha.

Plots were randomly arranged with an area of 30 m^2 (4.2 m × 7.2 m). In each plot, 3 rows in the middle were reserved to measure yields, and 2 rows on each side were for collecting soil and plant samples. The two-year experimental site was seeded in 2016 on May 7, 2016, and harvested on September 28, and sown again on May 11, 2017, and harvested on September 24. Diseases, pests, and weeds were controlled by managers as required.

Plant and soil sampling and analytical methods. Soil and soil water samples at five depths were collected at seven growth stages: before seedling (0 days after planting or DAP), 7 DAP, seedling (20 DAP), jointing (40 DAP), V12 (68 DAP), silking (100 DAP), and maturity (130 DAP). Three soil samples in every growth stage were collected randomly from each plot at 0–20, 20–40, 40–60, 60–80, 80–100 cm, and air-dried, ground and sieved (2.0 mm and 0.25 mm).

At 20, 40, 68, 100 and 130 days after seeding, five randomly selected plants in each plot were harvested by cutting at the ground surface and separated into stems (including cobs), leaves, and grain. In the laboratory, plant samples were placed in an oven for 30 min at 105 °C to deactivate enzymes, then dried at 75 °C to a constant weight, then weighed, followed by grinding the samples to pass through a 2 mm sieve.

The soil samples were extracted with 0.01 mol/L $CaCl_2$ for NO_3^--N and NH_4^+-N analyses using an AA3-A001-02E Auto-analyser (Bran-Luebbe, Norderstedt, Germany). The total plant N concentration was determined by H_2SO_4-H_2O_2 digestion and the AA3-A001-02E Auto-analyser (Feng et al. 2019).

Plant nitrogen uptake was calculated based on the resulting plant nitrogen concentrations and weights of different plant parts. Total apparent nitrogen use efficiency was calculated by the formula of Devkota et al. (2013), where total apparent nitrogen use efficiency (%) = (plant total nitrogen uptake from nitrogen treatment – the total nitrogen uptake in no nitrogen fertiliser treatment)/total applied nitrogen rate in the nitrogen treatment × 100. Nitrogen accumulation amount (NAA, kg/ha) = dry matter mass (straw, grain) per unit area of a certain growth period × nitrogen content. Nitrogen translocation amount (NTA, kg/ha) = nitrogen accumulation during flowering-nitrogen accumulation during maturity. Assimilated amount of nitrogen after anthesis (AANAA, kg/ha) = nitrogen accumulation during maturity-nitrogen transport in vegetative organs. Net soil nitrogen mineralisation (kg/ha) = crop nitrogen uptake in non-nitrogen application area + residual inorganic nitrogen in non-nitrogen application area – initial inorganic nitrogen accumulation in the non-nitrogen application area (Ju et al. 2007). Fertiliser nitrogen release (kg/ha) = crop uptake in nitrogen application zone + soil inorganic nitrogen residue in nitrogen application zone – initial inorganic nitrogen accumulation in soil-net nitrogen mineralisation.

Maize grain yields were measured by harvesting each area at the end of the growing season and grain weights adjusted to 140 g/kg moisture content.

Statistical analyses. Microsoft Excel 2013 (Microsoft, Redmond, USA) was adopted for data processing, and Origin 2017 (Originlab, Northampton, USA) was used to draw figures. All data were subjected to one-way analyses of variance (ANOVAs) followed by mean comparisons using Duncan's multiple range test ($P < 0.05$). Two-way ANOVA was used to investigate the interaction between fertiliser treatment and year. Analysis of variance and mean separation tests (Duncan's multiple range test) was performed using Statistical Analysis System package, version 9.2 (2010, SAS Institute, Cary, USA).

RESULTS AND DISCUSSION

The essence of high maize yield and nutrient efficiency is that nutrient supply and crop demand are matched, synchronised in time, and spatially consistent (Mi et al. 2018). The correlation between the release of slow/controlled-release fertiliser and spring maize cumulative nitrogen uptake was significantly higher than for urea, but both had a significant linear positive correlation over two years (Figure 1). The correlations are F1 > F4 > F3 > F2 (2016) and F4 > F1 > F3 > F2 (2017), respectively. The F4 treatment had the largest R^2 variation in two years.

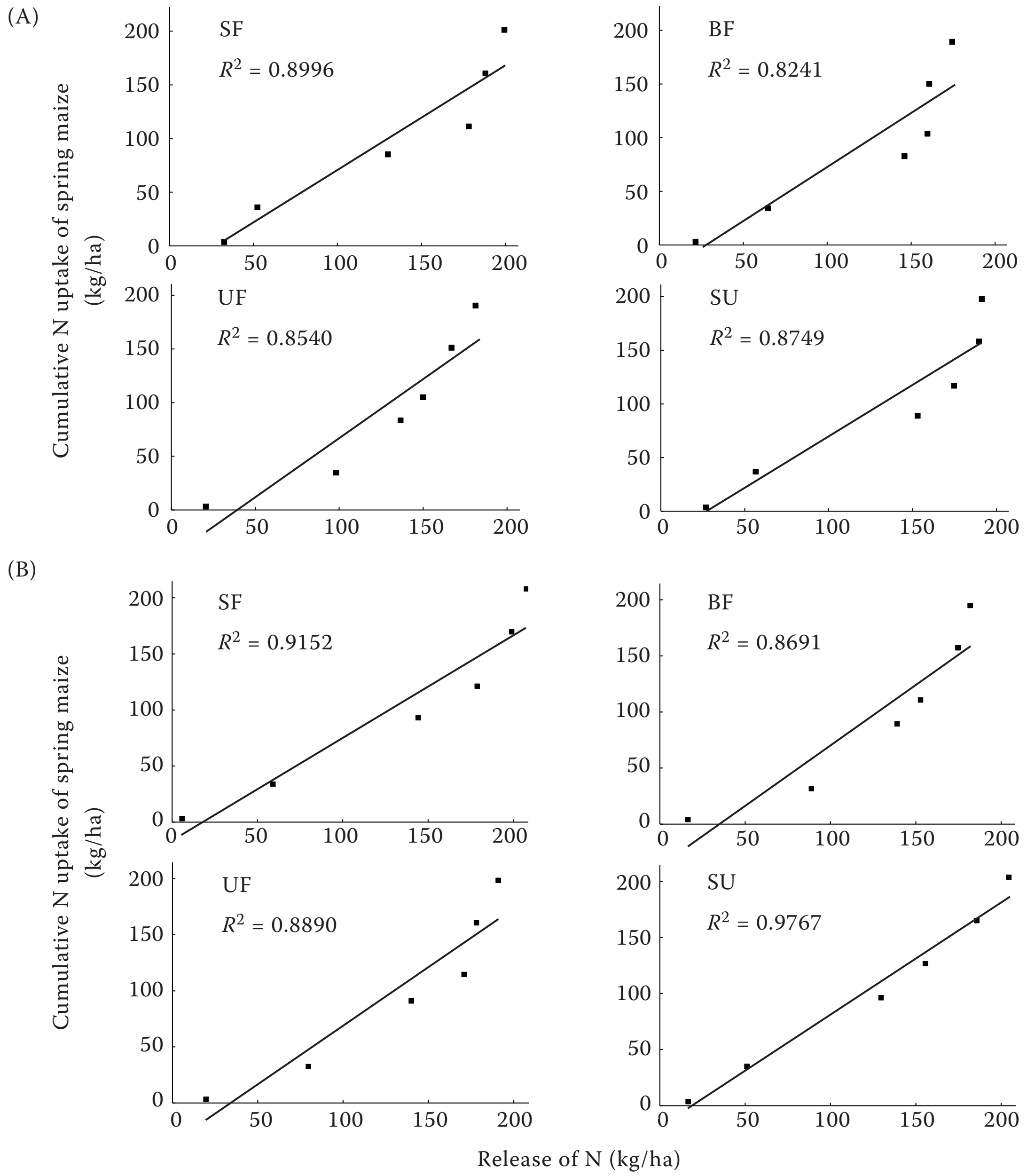

Figure 1. Relationships between nitrogen (N) release of controlled-release nitrogen fertilisers and N uptake of maize in (A) 2016 and (B) 2017. SF – stabilised fertiliser; BF – biochar-based compound fertiliser; UF – urea-formaldehyde; SU – sulfur-coated urea

Additionally, according to monthly records from the 21 meteorological stations in Liaoning province, during the corn growing season in 2016 and 2017, the monthly average temperature and most of the monthly mean rainfall were similar to the past 30 year's trends (Figure 2). While the monthly mean rainfall significantly exceeded the previous year in May to July 2016 (Figure 2). Studies have shown that sulfur-coated urea nutrient release is greatly influenced by soil moisture and temperature (Zheng et al. 2016). Among the fertilisers, F1 (urea with a nitrification urease and inhibitor) treatment was the most stable and performed the best over the two years. Therefore, we concluded that the stabilised fertiliser is the most suitable for the promotion and application in spring maize in the northeast of China.

The level of inorganic nitrogen in the soil can reflect the recent nitrogen supply capacity to a certain extent (Wu and Tan 2018). Zheng et al. (2016) showed that nitrogen release from slow-release nitrogen fertiliser was consistent with crop nitrogen fertiliser demand for the entire growing season, especially the soil inorganic nitrogen content, which increased at the later crop stages. Mi et al. (2018) also pointed out that compared with the same amount of urea, slow/controlled-release nitrogen can significantly increase the content of inorganic nitrogen in the middle and late crop stages. With absorption, utilisation and transformation of maize, the inorganic N content in the 0–20 cm and 20–40 cm soil layers of each treatment showed an initial decrease and then a slight upward trend (Figure 3). Controlled-release nitrogen fertiliser treatment significantly increased soil inorganic nitrogen content more than in the CK1 and CK2 treatments in the middle and later maize growth stages (Figure 3). However, the inorganic nitrogen content in the soil layer of the slow/controlled-release nitrogen (60–100 cm) treatment after maize harvest was lower than that of urea. Slow/controlled-release nitrogen can reduce the volatilisation of nitrogen and the loss of soil inorganic nitrogen to deep leaching by prolonging the nutrient release cycle (Zheng et al. 2017). Jia et al. (2014) believed that crops require less nitrogen in the early stages of growth and significantly increase nitrogen demand in the middle and late stages of growth, so it is vital to improving soil inorganic nitrogen content in this period for high crop yield and environmental safety. Among treatments, the sulfur-coated urea (F4) fertiliser had the highest inorganic nitrogen in the shooting to the bell-mouthed stage and the maturity period, whereas the stabilised fertiliser (F1) was the highest in the heading to filling stage (Figure 3).

Crop nitrogen uptake is the basis of crop photosynthetic activity and is, therefore, closely related to crop yield. Li et al. (2018) showed that slow/controlled-release nitrogen fertiliser could increase nitrogen absorption in middle and late maize growth stages. We have shown that maize nitrogen accumulation from the seedling to the heading stage was the highest with urea treatment, while from the filling to maturity stage, it was lower than the slow/controlled-release nitrogen treatment (Table 2). However, nitrogen accumulation also differed among different slow/controlled-release nitrogen treatments. Sulfur-coated urea treatment had the highest nitrogen accumulation before the maize heading stage, while after flowering, it declined, which may be because sulfur-coated urea nutrient release is greatly influenced by soil moisture and temperature (He et al. 2010, Zheng et al. 2016). If the temperature or moisture is too high, it will accelerate soil nutrient release and eventually lead to an inability to meet nitrogen demand after flowering. Additionally, according to monthly records from the 21 meteorological stations in Liaoning province, the monthly mean rainfall significantly exceeded the previous year in May to July 2016 (Figure 2). However, the monthly rainfall in the early stage of corn growth resulted in the rapid release of nutrients from coated urea and accelerated leaching of soil inorganic nitrogen into the deep soil, resulting in insufficient nutrient supply in the later stage of corn growth. Urea-formaldehyde fertiliser and biochar-based compound fertiliser treatments had lower nitrogen accumulation rates in the early stages of growth, although an increase in the later stages of growth occurred, but it was lower than that of stabilised fertiliser in the maturity stage. The reason may be that for maize, urea-formaldehyde fertiliser and biochar-based compound fertiliser are not only affected by environmental conditions but

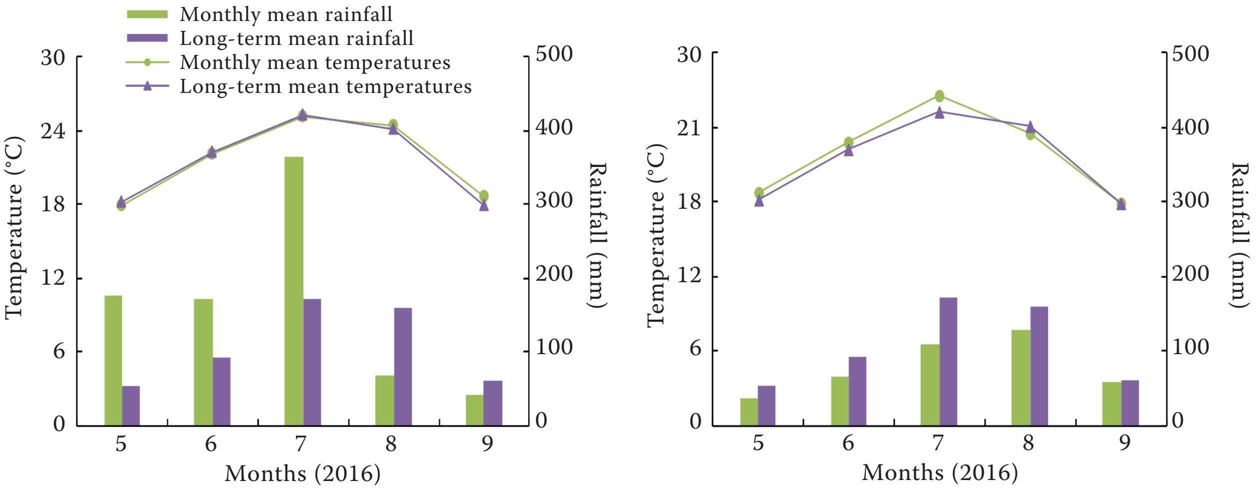

Figure 2. Monthly mean rainfall and mean temperatures during the spring maize growing season from 2016 to 2017 and long-term mean in Shenyang, China

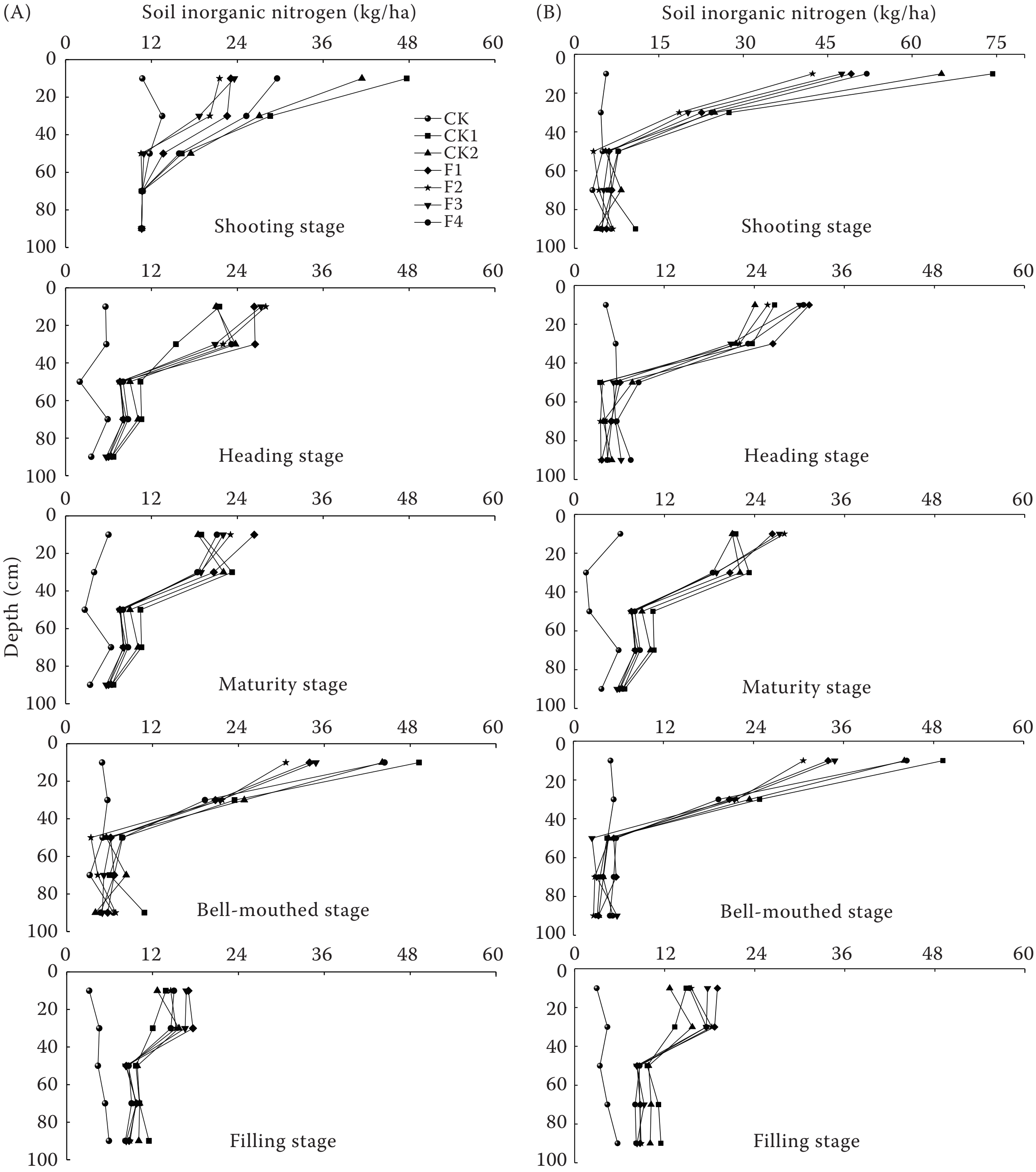

Figure 3. The dynamic changes of inorganic nitrogen contents in 0–100 cm soil under different nitrogen fertilisation treatments during the growing season of spring maize in (A) 2016 and (B) 2017; CK – no nitrogen fertiliser; CK1 – common application of urea; CK2 – 90% conventional urea control treatment; F1 – urea with a nitrification urease and inhibitor; F2 – urea-formaldehyde; F3 – compound fertiliser coated with biochar; F4 – sulfur-coated urea

also need to be degraded by microorganisms before they can be absorbed and used by plants (Gu et al. 2008). To some extent, the early demand for nitrogen could inhibit maize growth, but it could also affect nitrogen accumulation in the late maize growth stages. However, nitrogen release from stabilised fertiliser is less affected by temperature changes, soil moisture, pH, and soil biological activity for slow, stable continuous-

Table 2. Effects of different nitrogen (N) treatments on nitrogen accumulation characteristics of spring maize

Treatment		N accumulation (kg/ha)					PANA (kg/ha)	PPANA (%)	AANAA (kg/ha)
		V6	V12	VT	R3	R6			
2016	CK	22.5^{e}	57.4^{f}	84.8^{d}	97.2^{c}	129.3^{d}	44.5^{e}	34^{c}	31.5^{d}
	CK1	42.6^{a}	97.1^{a}	123.0^{a}	153.7^{b}	172.6^{c}	49.6^{d}	29^{d}	42.1^{c}
	CK2	40.5^{b}	92.4^{b}	119.3^{ab}	149.3^{bc}	166.6^{cd}	47.3^{d}	28^{d}	41.0^{c}
	F1	35.9^{cd}	85.2^{d}	111.2^{b}	160.6^{a}	201.2^{a}	90.0^{a}	45^{a}	78.3^{a}
	F2	34.1^{d}	82.6^{e}	103.6^{bc}	150.0^{bc}	189.3^{b}	85.7^{b}	45^{a}	77.6^{a}
	F3	34.7^{d}	83.4^{e}	105.0^{bc}	151.0^{bc}	190.4^{b}	85.0^{b}	45^{a}	76.1^{ab}
	F4	36.9^{c}	88.9^{c}	116.9^{ac}	158.1^{ab}	197.6^{ab}	80.7^{c}	41^{b}	73.1^{b}
2017	CK	20.1^{f}	55.2^{f}	78.9^{d}	94.4^{d}	118.7^{d}	39.8^{e}	34^{c}	24.9^{d}
	CK1	43.0^{a}	108.3^{a}	126.2^{a}	159.1^{bc}	179.8^{c}	53.6^{d}	30^{d}	44.5^{c}
	CK2	39.3^{b}	101.6^{b}	120.4^{b}	156.2^{c}	173.4^{cc}	53.0^{d}	31^{d}	45.3^{c}
	F1	33.7^{d}	92.9^{d}	121.2^{b}	169.6^{a}	207.9^{a}	86.7^{a}	42^{a}	76.0^{a}
	F2	31.7^{e}	89.3^{d}	110.6^{c}	157.1^{c}	194.9^{b}	84.3^{b}	43^{a}	73.7^{ab}
	F3	32.4^{e}	90.9^{e}	114.5^{c}	160.5^{bc}	198.4^{b}	83.9^{b}	42^{a}	74.9^{ab}
	F4	35.1^{c}	96.2^{c}	126.5^{a}	164.9^{b}	203.4^{ab}	76.9^{c}	38^{b}	65.1^{b}
ANOVA									
Year (Y)		**	**	**	**	**	**	ns	**
Fertilisation (F)		**	**	**	**	**	**	**	**
Y × F		ns	**	**	**	**	**	ns	**

ns – non-significant; *P < 0.05; **P < 0.01. Values followed by different small letters within a column are significantly different at P < 0.05; V6 – shooting stage; V12 – bell-mouthed stage; VT – heading stage; R3 – filling stage; R6 – maturity stage; PANA – post-anthesis nitrogen accumulation; PPANA – proportion of post-anthesis nitrogen accumulation; AANAA – assimilating amount of nitrogen after anthesis; CK – no nitrogen fertiliser; CK1 – common application of urea; CK2 – 90% conventional urea control treatment; F1 – urea with a nitrification urease and inhibitor; F2 – urea-formaldehyde; F3 – compound fertiliser coated with biochar; F4 – sulfur-coated urea

release (Zhao et al. 2003). This can meet the nutrient requirements of different maize growth stages and the production of various vegetative organs, maintain vitality, delay senescence, promote grain filling, and significantly increase grain nitrogen content and NUE at the maturity stage. Wang et al. (2013) showed that nitrogen accumulation had a significant effect on crop yield after flowering. Compared with other slow-release nitrogen fertiliser treatments, stabilised fertiliser (F1) treatment increased the nitrogen accumulation and assimilation amount after flowering by 4.3–9.3% and 0.7–5.2% (2016); 2.4–9.8% and 1.1–10.9% (2017), respectively (Table 2). Additionally, we found that the treatments with high maize grain yields had corresponding high total nitrogen accumulation and nitrogen accumulation after flowering.

One of the goals of sustainable green development of agriculture in China is to make efforts to transform the current agriculture with high nitrogen rate input and low unit yield to green planting and production with high productivity, high resource utilisation efficiency and low environmental impact (Pan et al. 2020). Fertiliser is the key to high maize yield, which is one of the important indicators of experiment success (Cui et al. 2008). We showed that with 10% nitrogen reduction, the differences in corn yield between slow/controlled-release nitrogen fertiliser and CK1 treatment were insignificant (Table 3, Figure 4). Furthermore, the stabilised fertiliser (F1) treatment dramatically increased grain yield, NUE, and nitrogen accumulation at each maize growth stage. Grain yield increased by 2.32% and 11.33% (2016), and 1.55% and 7.87% (2017), respectively, when compared with the urea CK1 and CK2 treatments (Table 3). In particular, in 2017, the CK treatment was infected with *Ustilago maydis* in the late grain filling stage, which disrupted the normal grain filling and caused a reduction in production. Advantages in the use of slow-release fertiliser include: reducing fertiliser input and production cost, solving late maize fertiliser

Table 3. The maize yield and nitrogen use efficiency (NUE) under different N fertiliser treatments

Year	Treatment	Yield (kg/ha)	Increased rate (%)		NUE (%)
			compared to CK1	compared to CK2	
2016	CK	8 597^{c}	–	–	–
	CK1	10 886^{ab}	–	8.81	18.6^{c}
	CK2	10 005^{b}	−8.09	–	17.8^{c}
	F1	11 139^{a}	2.32	11.33	34.2^{a}
	F2	10 716^{ab}	−1.56	7.11	28.6^{b}
	F3	10 849^{ab}	−0.34	8.44	29.1^{b}
	F4	10 501^{ab}	−3.54	4.96	32.5^{ab}
2017	CK	2 156^{c}	–	–	–
	CK1	11 117^{ab}	–	6.23	26.2^{d}
	CK2	10 465^{ab}	−5.86	–	26.1^{d}
	F1	11 289^{a}	1.55	7.87	42.5^{a}
	F2	9 306^{b}	−16.29	−11.01	36.3^{c}
	F3	9 652^{ab}	−13.18	−7.77	38.0^{c}
	F4	11 152^{ab}	0.31	6.56	40.3^{b}
ANOVA					
Year (Y)		**	–	–	**
Fertilisation (F)		**	–	–	**
Y × F		**	–	–	ns

ns – non-significant; *P < 0.05; **P < 0.01. Values followed by different small letters within a column are significantly different at P < 0.05; CK – no nitrogen fertiliser; CK1 – common application of urea; CK2 – 90% conventional urea control treatment; F1 – urea with a nitrification urease and inhibitor; F2 – urea-formaldehyde; F3 – compound fertiliser coated with biochar; F4 – sulfur-coated urea

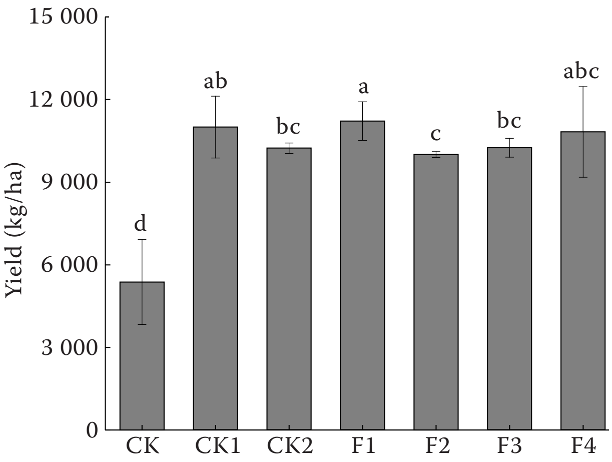

Figure 4. Effects of different nitrogen treatments on two-year average yield. CK – no nitrogen fertiliser; CK1 – common application of urea; CK2 – 90% conventional urea control treatment; F1 – urea with a nitrification urease and inhibitor; F2 – urea-formaldehyde; F3 – compound fertiliser coated with biochar; F4 – sulfur-coated urea. Different small letters within a column are significantly different at P < 0.05

difficulties and the shortage of the rural labor force, improving economic and social benefits, and facilitating its widespread popularity and application to field crops. Among them, the F1 treatment performed the best.

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