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Improving the growth, lodging and yield of different density-resistance maize by optimising planting density and nitrogen fertilisation

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Abstract: Matching the planting density, fertilisation, and genotype is crucial to improve the maize yield. Here, two-year field trials, including 4 densities and 3 nitrogen (N) rates for 2 maize cultivars, were conducted to study the effects of planting density and N rate on maize growth, lodging, spike characters, and yield. Compared with 360 kg/ha, N application of 180 kg/ha decreased the plant, ear height, and stem circumference of WeiKe 702 (WK702), while increased the plant height and stem circumference, but decreased ear height of ZhongDan 909 (ZD909). Meanwhile, the N application of 180 kg/ha greatly reduced the lodging rates of maize under the high density. The maize yield increased and reached the maximum yield at 7.5×10^4 plant/ha, and then decreased with increasing density. The N application of 180 kg/ha increased yield by 0.49, 0.73, 5.38, 7.81% from low to high planting densities, and reduced the bald tip length by 18.86%. WK702 was more sensitive to the planting density and N application, with greater variation of yield and spike traits than ZD909 under the densification. Therefore, the N application of 180 kg/ha and a density of 7.5×10^4 plant/ha could improve maize growth and lodging, and therefore increase maize yield.

Keywords: *Zea mays* L.; crop population; excess fertilisation; competition; agronomic characteristics

The establishment of favourable crop population structure by optimising the planting density was important to make rational use of photosynthetic resources and achieve the yield potential (Tollenaar and Lee 2002, Assefa et al. 2016). Many researches have indicated reasonable densification could promote ear development, plant traits, root growth, photosynthetic characteristics, matter accumulation, nutrient absorption, and then grain yield (Cuomo et al. 1998, Song et al. 2016, Shao et al. 2018). However, too high population density might cause intense individual competition and adverse effects on the crop photosynthesis, nutrient absorption, at the same time, more plant diseases and insect pests, lodging, empty rod, bald tip, lack of grain (Gonzalez et al. 2018).

The nitrogen (N) fertiliser application was an important measure to improve maize yield by promoting maize growth, increasing chlorophyll content and net photosynthetic rate, extending the photosynthetic duration of leaves, promoting dry matter accumulation and transfer, nutrient absorption, and grain filling (Liu et al. 2009, Qiu et al. 2015). However, the yield might decrease when the N application exceeded the optimal N rate. Over application of N fertiliser led to excessive metabolism of nutrients, reduced photosynthetic rate, and the accumulation of assimilates, although the leaf area was increased (He et al. 1998). The N transported to grains, the physiological and agronomic efficiency of N fertiliser was also reduced, which was not conducive to high yield (Zhao et al. 2017). Also, due to the N excessive application, shading caused longer time to grow for meristem of internode meristem, make the stem cells larger and the cell walls thinner, which was easy to

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cause diseases, insect pests, and lodging risk (Quang Duy et al. 2004, Zhang et al. 2014). Moreover, during the short growth period of maize with high temperature and much rainfall, the excessive N application and low N use efficiency might accelerate the active N loss and environmental pollution (Wang et al. 2014).

At present, there are both insufficient density and excessive N application in the actual maize production in China. In China, the planting density of maize was relatively low due to other restrictions in maize production, such as cultivation techniques, cultivars, irrigation, fertiliser, and mechanisation. In the 1950s, the average planting density was only 15 000–22 500 plants/ha. The planting density increased gradually with the improvement of the above limiting factors and increased to more than 30 000 plants/ha in the 1960s because of the development of cultivation technology. Subsequently, densification planting was further recognised by farmers due to the development of cultivar breeding, the extension of erectophile and dense-resistant maize, and the input increase such as water and fertiliser. By the 2010s, the planting density of the horizontal-leaf cultivars was generally 45 000 plant/ha, and that of the dense-tolerant cultivars could reach 60 000 plants/ha. Nevertheless, with the popularisation of maize harvesting mechanisation, the planting density in China still needed to be further improved (Li and Wang 2010). For example, the planting density of maize in North China Plain, an important maize production area, was 5.25–6.00 × 10^4 plants/ha, which was far lower than the average level of 8.55–10.95 × 10^4 plants/ha in the United States (Ming et al. 2017).

Before the 1980s in China, the nutrient input in crop production was mainly based on farmyard manure. However, the consumption of chemical fertiliser increases rapidly due to the obvious effect of increasing yield. In China, the field for agricultural production was scattered and small, which was operated by smallholder farmers with a low educational level. Therefore, farmers would like to increase the input of fertilisers in order to reduce the risk of yield reduction, and seldom considered the economic benefits and environmental risks, which led to the common excessive application of chemical fertiliser in recent years (Zhang et al. 2016). The N fertiliser application for high yield maize in North China Plain could be as high as 458 kg/ha while the N fertiliser recovery efficiency averaged less than 40% (Li et al. 2009).

In recent years, there have been many studies on N fertilisation and planting density for maize, indicating that the density and N application not only affected the yield but also had obvious interaction (Sheng et al. 2010, Ciampitti et al. 2013). Generally, the planting density should be sparsely in the field with a small fertiliser application amount while dense in the field with a large fertiliser application rate. However, the high N application would aggravate the problems of maize diseases, insect pests, and lodging, and lead to the decline of maize yield and N efficiency when the density was high.

It is hypothesised that the negative effect caused by the density increase could be compensated by reasonable N fertiliser application, and the complementary advantages could be realised by increasing density and decreasing N fertiliser, so as to improve the growth characteristics and yield of maize. Therefore, through a 2-year field experiment, this study was to evaluate the effects of N application rate on the growth traits, lodging, ear character, and yield of summer maize under increased planting density in North China Plain, so as to achieve a high yield of maize and high efficiency of N fertiliser applied.

MATERIAL AND METHODS

Field site. The experiment was conducted in Yuzhou city, China (34°26'N, 113°34'E). The soil type was Fluventic Ustochrept according to the USDA soil taxonomic system with the clay texture. The basic properties of surface layer soil (0–20 cm) before sowing was 8.2 for pH, 1.04 g/kg for total N, 9.45 g/kg organic carbon, 113.7 mg/kg for available potassium, 20.0 mg/kg for available phosphorus, 1.43 g/cm^3 for bulk density. The cropping system was typical winter wheat-summer maize rotation, and the straw was returned to the soil before rotary tillage.

Experiment design. The experiment was carried out in the maize season from June to October in 2015–2016. There were two maize cultivars of WeiKe702 (WK702) and ZhongDan909 (ZD909). These two maize cultivars were widely planted in North China Plain as summer maize. The growth periods from seedling to maturity were all about 100 days with compact plant types and good stay-green. Four densities of 4.5 (D45), 6.0 (D60), 7.5 (D75) and 9.0 (D90) × 10^4 plant/ha, and three N fertiliser levels of control with N omission (N0), low (180 kg/ha, N180), and high N fertiliser (360 kg/ha, N360), were set. There were 3 replications for each treatment with randomised block design. The plot area was 5 m × 6 m = 30 m^2.

The N fertiliser used in the experiment was urea (N 46.4%). The P and K fertilisers were superphos-

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phate (P 5.2%) and potassium chloride (K 49.8%) with the dosages of 39.3 and 74.7 kg/ha. Half of N and all P and K fertiliser were applied as base fertiliser, and half of N fertiliser was applied in the V12 stage. In 2015 and 2016, seeds were artificially planted on June 11, with a row spacing of 0.6 m. The thinning and singling were conducted in the three-leaf (V3) stage of maize, and the harvest was on September 20.

Sampling and measuring. At the maturity stage of maize, 5 consecutive maize plants were selected from each plot, and their plant height, spike height, and stem base circumference were determined. At the time of the mature maize stage, 40 consecutive plants were harvested in each plot, and 10 representative maize ears with uniform growth were selected for seed examination to investigate ear length, ear thickness, bald tip length, row number, and grain number per row. Maize lodging was observed in 2016, and the lodging rate was investigated and calculated (lodging rate = the number of fallen plants/total plants × 100%).

Date treatment and analysis. The date treatment was finished in soft of Microsoft Excel 2010 (Redmond, USA), and statistical analysis was conducted in SPSS 20.0 (Armonk, USA). The significance test was at a 5% level with the Duncan method.

RESULTS

Plant height. The plant height of two cultivars of maize was significantly higher in 2016 than in 2015 (Figure 1). In two years, the plant height increased with the increase in planting density. The increase of plant height was small before the density reached D75, but was large when the density increased from D75 to D90. Compared with N360, the N180 reduced the maize plant height of WK702 but increased the plant height of ZD909.

Ear height. In line with the trend of plant height, ear height of maize was higher in 2016 than 2015 and showed an increasing trend with increasing planting density (Figure 2). The increase of ear height was smaller at low density while it was the largest when planting density increased from D60 to D75. Under the same density, the ear height of maize decreased for N180 fertilisation compared with N360 treatment.

Stem circumference. The stem base circumference decreased gradually with increasing density (Figure 3). The difference of stem base circumference of the two cultivars between treatment without N application (N0) and N application (N180 and N360) was smaller in 2015 than in 2016. Under the same density, N180 decreased the base circumference of the maize stem of WK702 but increased the circumference of ZD909 compared with N360 treatment.

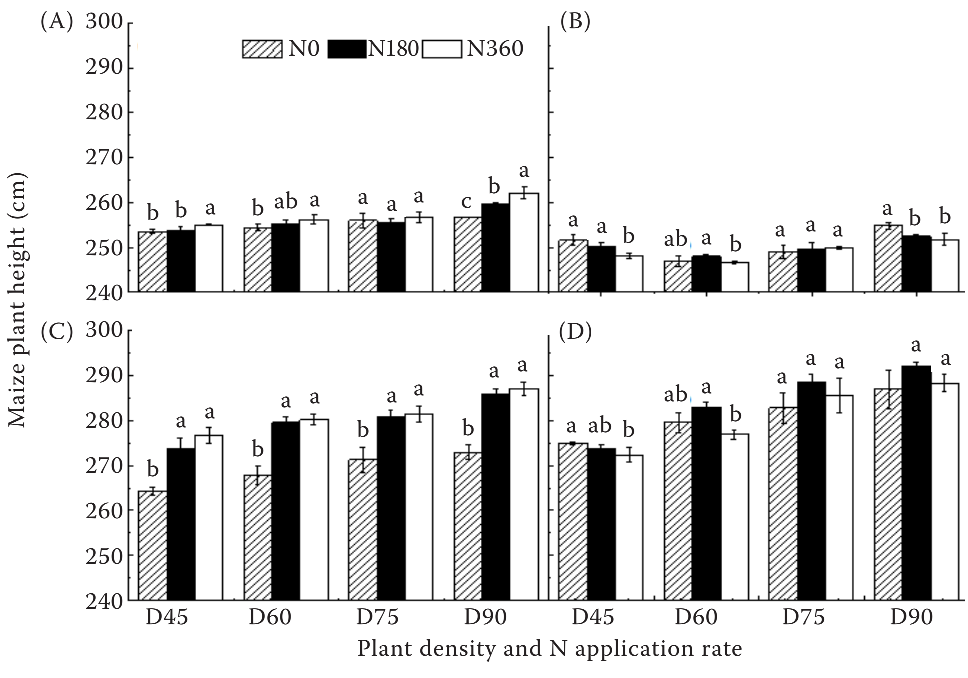

Figure 1. Effects of planting density and nitrogen (N) rate on plant height. (A) 2015 – WK702; (B) 2015 – ZD909; (C) 2016 – WK702, and (D) 2016 – ZD909. Vertical bars denote the standard deviation of the mean. Different letters indicate significant differences ($P < 0.05$) between N rates within the same plant density. N0 – control; N180 – 180 kg N/ha; N360 – 360 kg N/ha; D45 – 4.5, D60 – 6.0, D75 – 7.5, D90 – 9.0 × 10^4 plant/ha

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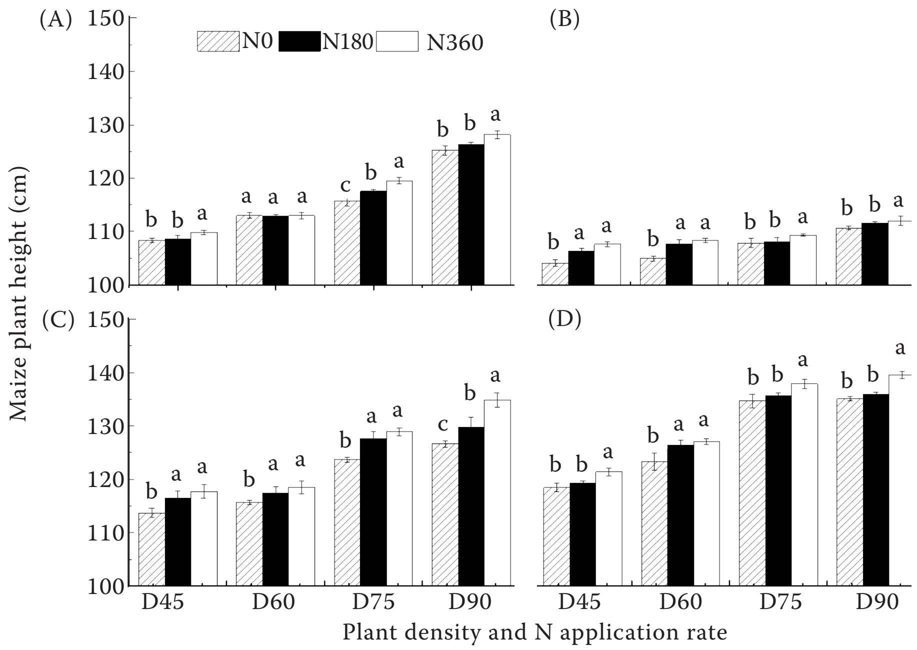

Figure 2. Effects of planting density and nitrogen (N) rate on ear height. (A) 2015 – WK702; (B) 2015 – ZD909; (C) 2016 – WK702, and (D) 2016 – ZD909. Vertical bars denote the standard deviation of the mean. Different letters indicate significant differences (P < 0.05) between N rates within the same plant density. N0 – control; N180 – 180 kg N/ha; N360 – 360 kg N/ha; D45 – 4.5, D60 – 6.0, D75 – 7.5, D90 – 9.0 × 10^4 plant/ha

Lodging rate. In 2016, the lodging rate of WK702 was much higher than ZD909, and the lodging rate of two cultivars showed a decreasing first and then increasing trend with the increasing density (Figure 4). Under the low density of D45 and D60, the lodging rate of WK702 significantly decreased with the increase of N application amount; when the density reached D75 and D90, the lodging rate for N360 was higher than N180. There was no difference in the lodging rate of ZD909 between N360 and N180 treatment under the low density of D45, but showed as N360 > N180 under higher density than D45.

Ear traits. From the spike characters, the variation of bald tip length under different densities and N rates was the largest, followed by the grain number per row and spike length, while the variation of spike width and row number was smaller (Table 1). The variation of WK702 was higher than ZD909. Under the same N application, the spike length, spike width, row number, and grain number per row decreased, but the length of the bald tip increased with the increasing density. Under the same density, the length of the bald tip was significantly lower under the N180 than N360 treatment, with 21.94% lower for WK702 and 15.79% for ZD909. The spike length of WK702 showed an increasing trend, with an increase of 2.18% in two years, especially a high increase of 5.5% at D90. The spike length of ZD909 increased by 3.47% on average in 2015 but decreased by 0.82% in 2016. The grain per row increased by 3.69% for WK702, with a high increase of 7.69% at D75 and D90, but showed a small change for ZD909. The effect of N rate on spike width and row number was small.

Grain yield. Under the same N application, the yield of two maize cultivars first increased but did not further increase or decreased significantly after reaching D75 (Figure 5). The yield of WK702 decreased by 11.47% at a density of D90 compared with D75 under N360 treatment, while only increased by 1.61% for ZD909. Compared with the N360, N180 improved the maize yield, and the effect heightened with the increase of density: the yield of two cultivars averagely increased by 0.49, 0.73, 5.38, and 7.81% under D45, D60, D75, and D90, respectively. There were also differences between the two cultivars: under high-density conditions, the N180 application could increase the yield by 17.28% for WK702, while –1.65% for ZD909.

DISCUSSION

In this study, the abundant rainfall in the maize growing season and the high plant and ear height led to the maize lodging in 2016. The lodging risk was associated with planting density and N fertilisation.

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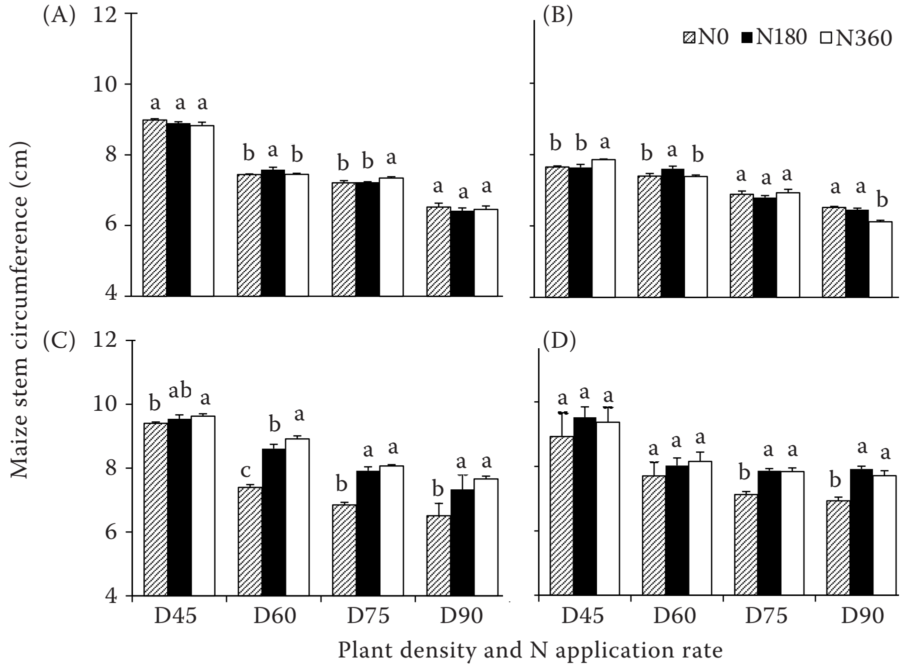

Figure 3. Effects of planting density and nitrogen (N) rate on stem basal circumference. (A) 2015 – WK702; (B) 2015 – ZD909; (C) 2016 – WK702, and (D) 2016 – ZD909. Vertical bars denote the standard deviation of the mean. Different letters indicate significant differences (P < 0.05) between N rates within the same plant density. N0 – control; N180 – 180 kg N/ha; N360 – 360 kg N/ha; D45 – 4.5, D60 – 6.0, D75 – 7.5, D90 – 9.0 × 10^4 plant/ha

Consistent with the previous results (Solomon et al. 2017), it was found that the lodging rate of maize was increased under both high density and N application. This was probably related to the increase in plant and ear height and the decline of stem circumference at high density. Meanwhile, excessive application of N might result in a high risk of lodging rate, especially under high planting density, because it promoted the increase of spike and plant height of maize, the decrease of stem diameter (Shi et al. 2016). Therefore, under the condition of densification, the lodging rate of maize could be significantly reduced by applying low N fertiliser. However, the lodging rate of maize also increased to a certain extent, when the density was too low at 4.5 × 10^4 plant/ha, especially without N fertiliser. Studies have shown that the anti-inverted mechanical properties of maize, for example, dry weight between internodes, dry weight per unit stem length, puncture strength of hard skin, and bending ability of maize stalks, all increased first and then decreased with increasing maize population (Brekke et al. 2011), which might be related to the high lodg-

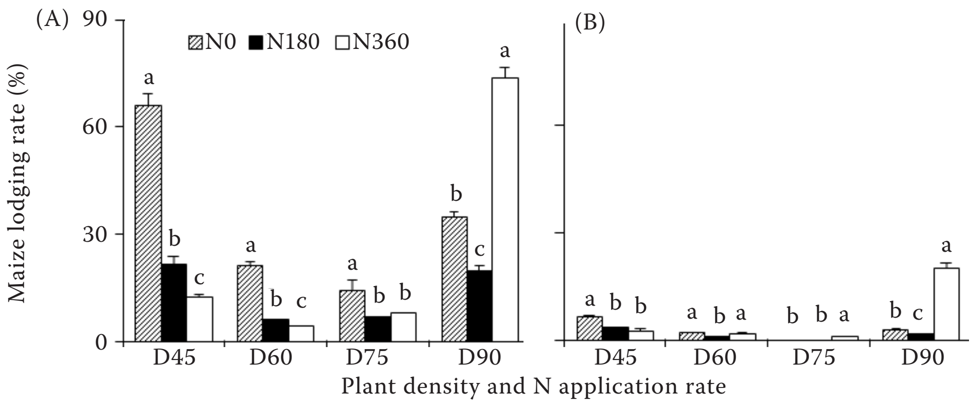

Figure 4. Effects of planting density and nitrogen (N) rate on lodging rate. (A) 2016 – WK702, and (B) 2016 – ZD909. Vertical bars denote the standard deviation of the mean. Different letters indicate significant differences (P < 0.05) between N rates within the same plant density. N0 – control; N180 – 180 kg N/ha; N360 – 360 kg N/ha; D45 – 4.5, D60 – 6.0, D75 – 7.5, D90 – 9.0 × 10^4 plant/ha

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Table 1. Effects of planting density and nitrogen (N) rate on ear traits

Year	Planting density	N fertiliser rate	WK702 spike length (cm)	WK702 spike width (cm)	WK702 bald tip length (cm)	WK702 row number	WK702 grain per row	ZD909 spike length (cm)	ZD909 spike width (cm)	ZD909 bald tip length (cm)	ZD909 row number	ZD909 grain per row
2015	D45	N0	20.72 ± 0.11^{ab}	5.49 ± 0.16^{b}	0.88 ± 0.08^{f}	15.47 ± 0.15^{bcd}	38.67 ± 0.32^{b}	20.76 ± 0.31^{bc}	5.28 ± 0.03^{abc}	0.88 ± 0.02^{g}	15.53 ± 0.15^{bcde}	40.03 ± 0.15^{b}
		N180	21.36 ± 0.22^{a}	5.76 ± 0.04^{a}	0.14 ± 0.05^{g}	15.73 ± 0.12^{abc}	40.93 ± 0.21^{a}	21.95 ± 0.23^{a}	5.56 ± 0.01^{a}	0.63 ± 0.03^{i}	15.80 ± 0.20^{bc}	40.97 ± 0.45^{ab}
		N360	21.26 ± 0.09^{a}	5.75 ± 0.01^{a}	0.20 ± 0.02^{g}	16.07 ± 0.05^{ab}	41.00 ± 0.20^{a}	21.30 ± 0.29^{ab}	5.50 ± 0.02^{ab}	0.69 ± 0.04^{hi}	16.53 ± 0.12^{a}	41.33 ± 0.15^{a}
	D60	N0	19.28 ± 0.23^{de}	5.35 ± 0.05^{bcd}	1.71 ± 0.04^{d}	15.57 ± 0.59^{abc}	34.30 ± 0.61^{d}	19.54 ± 0.36^{de}	5.16 ± 0.02^{abc}	1.75 ± 0.02^{cd}	15.53 ± 0.21^{bcde}	33.37 ± 0.40^{f}
		N180	20.24 ± 0.31^{bc}	5.47 ± 0.06^{b}	0.94 ± 0.06^{f}	15.53 ± 0.03^{bcd}	38.27 ± 0.38^{b}	20.28 ± 0.32^{cd}	5.27 ± 0.03^{abc}	0.81 ± 0.02^{gh}	15.27 ± 0.15^{def}	38.17 ± 0.21^{c}
		N360	19.86 ± 0.19^{cd}	5.46 ± 0.05^{b}	1.06 ± 0.04^{f}	15.34 ± 0.06^{cde}	38.53 ± 0.15^{b}	19.31 ± 0.22^{e}	5.30 ± 0.05^{abc}	1.09 ± 0.08^{f}	15.67 ± 0.12^{bcd}	35.77 ± 0.21^{de}
	D75	N0	18.56 ± 0.25^{ef}	5.39 ± 0.03^{bc}	2.24 ± 0.12^{c}	16.07 ± 0.12^{ab}	33.47 ± 0.50^{d}	18.94 ± 0.20^{e}	5.08 ± 0.06^{abc}	1.90 ± 0.01^{bc}	15.07 ± 0.23^{ef}	34.73 ± 0.35^{e}
		N180	19.25 ± 0.22^{de}	5.48 ± 0.03^{b}	1.49 ± 0.07^{e}	16.20 ± 0.10^{a}	36.33 ± 0.47^{c}	19.56 ± 0.33^{de}	5.22 ± 0.05^{abc}	1.32 ± 0.06^{e}	15.73 ± 0.12^{bc}	35.70 ± 0.26^{de}
		N360	19.11 ± 0.11^{de}	5.43 ± 0.03^{b}	1.68 ± 0.05^{d}	15.80 ± 0.10^{abc}	33.47 ± 0.32^{d}	18.90 ± 0.34^{e}	5.17 ± 0.04^{abc}	1.62 ± 0.03^{d}	15.40 ± 0.17^{cde}	36.80 ± 0.96^{d}
	D90	N0	15.69 ± 0.19^{h}	5.05 ± 0.05^{e}	3.04 ± 0.04^{a}	14.93 ± 0.06^{de}	24.77 ± 0.12^{g}	17.67 ± 0.22^{f}	4.97 ± 0.62^{bc}	2.36 ± 0.12^{a}	15.60 ± 0.26^{bcd}	29.37 ± 0.31^{g}
		N180	17.85 ± 0.22^{f}	5.22 ± 0.07^{cde}	2.62 ± 0.09^{b}	15.53 ± 0.31^{bcd}	31.03 ± 0.25^{e}	18.00 ± 0.27^{f}	5.02 ± 0.08^{bc}	1.91 ± 0.06^{bc}	16.00 ± 0.20^{b}	32.47 ± 0.42^{f}
		N360	16.99 ± 0.28^{g}	5.20 ± 0.04^{de}	2.99 ± 0.03^{a}	14.73 ± 0.16^{e}	27.00 ± 0.66^{f}	17.59 ± 0.23^{f}	4.94 ± 0.02^{c}	2.03 ± 0.06^{b}	14.93 ± 0.15^{ef}	32.63 ± 0.25^{f}
		CV ± SD	8.71 ± 1.61	3.80 ± 0.21	61.61 ± 0.97	3.02 ± 0.47	14.57 ± 5.07	7.05 ± 1.37	4.37 ± 0.24	40.31 ± 0.57	2.76 ± 0.44	10.01 ± 3.61
2016	D45	N0	20.40 ± 0.57^{d}	5.33 ± 0.16^{bc}	0.93 ± 0.66^{c}	15.93 ± 0.76^{abc}	39.90 ± 0.82^{bc}	20.29 ± 0.15^{c}	5.06 ± 0.20^{abc}	0.75 ± 0.04^{d}	15.67 ± 0.31^{bcd}	40.37 ± 0.21^{ab}
		N180	21.57 ± 0.46^{a}	5.50 ± 0.08^{ab}	0.10 ± 0.02^{e}	15.93 ± 0.76^{abc}	41.67 ± 0.21^{ab}	21.26 ± 0.19^{a}	5.20 ± 0.02^{a}	0.36 ± 0.03^{g}	16.00 ± 0.72^{ab}	42.17 ± 0.60^{a}
		N360	21.45 ± 0.52^{ab}	5.58 ± 0.03^{a}	0.26 ± 0.01^{de}	16.63 ± 0.64^{a}	41.93 ± 0.38^{a}	21.32 ± 0.12^{a}	5.18 ± 0.03^{a}	0.37 ± 0.03^{g}	16.40 ± 0.35^{a}	40.83 ± 0.32^{ab}
	D60	N0	20.66 ± 0.65^{cd}	5.18 ± 0.12^{cde}	0.64 ± 0.13^{cde}	15.80 ± 0.53^{abc}	38.40 ± 0.26^{cd}	20.28 ± 0.16^{c}	5.00 ± 0.10^{bcd}	0.88 ± 0.02^{c}	15.07 ± 0.31^{d}	39.30 ± 0.50^{bcd}
		N180	21.26 ± 0.44^{abc}	5.38 ± 0.02^{abc}	0.23 ± 0.03^{de}	15.87 ± 0.50^{abc}	41.00 ± 0.40^{ab}	20.55 ± 0.21^{bc}	5.15 ± 0.05^{ab}	0.22 ± 0.05^{h}	15.80 ± 0.20^{abc}	40.10 ± 0.70^{abc}
		N360	20.79 ± 0.06^{bcd}	5.39 ± 0.02^{abc}	0.31 ± 0.03^{cde}	16.53 ± 0.61^{a}	40.90 ± 0.10^{ab}	20.74 ± 0.20^{b}	5.08 ± 0.03^{abc}	0.51 ± 0.08^{f}	15.68 ± 0.10^{bcd}	39.87 ± 1.10^{bcd}
	D75	N0	18.55 ± 0.25^{fg}	4.98 ± 0.08^{ef}	1.82 ± 0.80^{ab}	15.50 ± 0.17^{bc}	33.23 ± 3.09^{g}	18.83 ± 0.18^{e}	4.86 ± 0.05^{def}	1.01 ± 0.09^{b}	15.67 ± 0.42^{bcd}	36.17 ± 2.08^{ef}
		N180	19.56 ± 0.17^{e}	5.10 ± 0.10^{def}	0.84 ± 0.60^{cd}	15.27 ± 0.23^{bc}	38.23 ± 0.55^{cd}	19.19 ± 0.09^{d}	4.98 ± 0.13^{cde}	0.60 ± 0.03^{e}	15.80 ± 0.20^{abc}	38.07 ± 0.85^{cde}
		N360	19.48 ± 0.30^{e}	5.28 ± 0.03^{cd}	0.95 ± 0.04^{c}	16.27 ± 0.21^{ab}	36.70 ± 0.26^{de}	19.38 ± 0.18^{d}	4.95 ± 0.06^{cde}	0.62 ± 0.04^{e}	15.07 ± 0.31^{d}	37.93 ± 2.06^{de}
	D90	N0	16.69 ± 0.09^{h}	4.97 ± 0.29^{ef}	2.41 ± 0.04^{a}	15.03 ± 0.35^{c}	29.23 ± 0.81^{h}	17.35 ± 0.13^{g}	4.70 ± 0.10^{g}	1.86 ± 0.09^{a}	15.20 ± 0.20^{cd}	32.83 ± 1.99^{g}
		N180	19.03 ± 0.08^{ef}	5.08 ± 0.08^{def}	1.68 ± 0.02^{b}	15.67 ± 0.31^{abc}	35.75 ± 0.58^{ef}	18.25 ± 0.13^{f}	4.80 ± 0.00^{fg}	1.01 ± 0.04^{b}	15.93 ± 0.42^{ab}	35.20 ± 0.44^{f}
		N360	17.95 ± 0.18^{g}	4.92 ± 0.08^{f}	1.90 ± 0.04^{ab}	15.07 ± 0.70^{c}	34.67 ± 0.31^{fg}	18.45 ± 0.33^{f}	4.84 ± 0.05^{efg}	1.06 ± 0.03^{b}	16.00 ± 0.20^{ab}	35.00 ± 0.26^{f}
		CV ± SD	7.63 ± 1.51	4.46 ± 0.23	79.71 ± 0.80	4.23 ± 0.67	10.26 ± 3.86	6.33 ± 1.24	3.33 ± 0.17	55.72 ± 0.43	2.95 ± 0.49	7.46 ± 2.90
Sources of variation												
Y (year)			**	**	**	ns	**	**	**	**	ns	**
D (density)			**	**	**	**	**	**	**	**	**	**
N (N rate)			**	**	**	ns	**	**	**	**	**	**
Y × D			**	*	**	*	**	**	ns	**	ns	**
Y × N			ns	ns	ns	**	*	**	ns	**	ns	ns
D × N			**	ns	ns	*	**	**	ns	**	**	*
Y × D × N			ns	ns	ns	ns	**	ns	ns	**	**	*

Data were shown as mean ± standard deviation (SD). Different letters indicate significant differences at $P < 0.05$ among different densities and N rates in the same year. *$P < 0.05$; **$P < 0.01$; ns – not significant; *CV* – coefficient of variation; N0 – control; N180 – 180 kg N/ha; N360 – 360 kg N/ha; D45 – 4.5, D60 – 6.0, D75 – 7.5, D90 – 9.0 × 10^4 plant/ha

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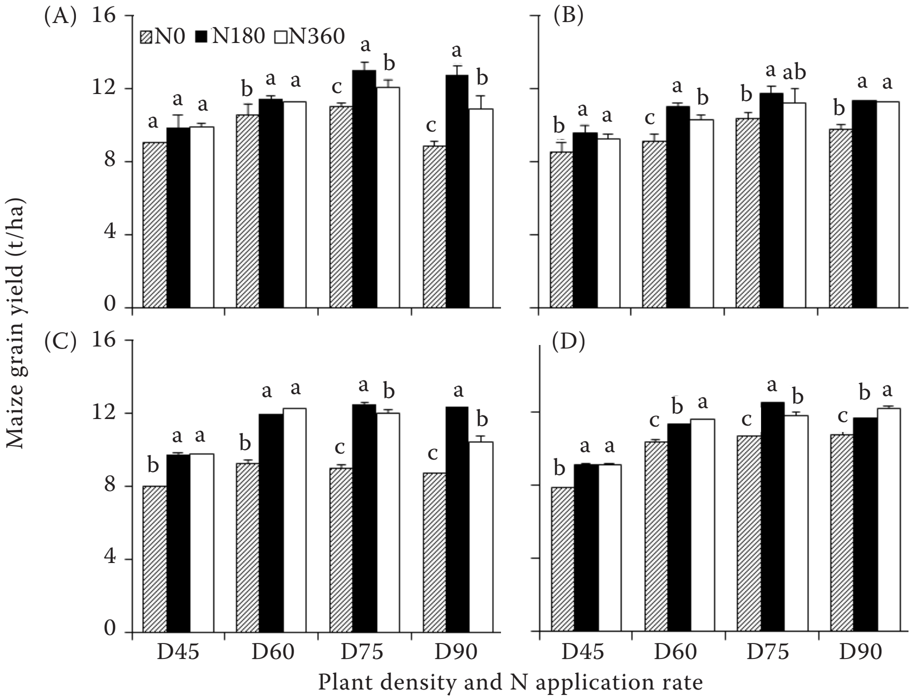

Figure 5. Effects of planting density and nitrogen (N) rate on yield. (A) 2015 – WK702; (B) 2015 – ZD909; (C) 2016 – WK702, and (D) 2016 – ZD909. Vertical bars denote the standard deviation of the mean. Different letters indicate significant differences ($P < 0.05$) between N rates within the same plant density. N0 – control; N180 – 180 kg N/ha; N360 – 360 kg N/ha; D45 – 4.5, D60 – 6.0, D75 – 7.5, D90 – 9.0 × 10^4 plant/ha

ing risk at too low and high planting density. At low density and N application, the weak root and stem of maize were weak to resist lodging (Ciampitti et al. 2013), while increasing N was beneficial to improve the nutrition and growth characteristics of maize, and reduced lodging.

Improving maize yield by planting density had to coordinate the relationship of spike number per unit area, grain number per spike, and grain weight. This study showed that increasing planting density could increase maize yield to a certain extent, mainly by making full use of the population advantages of the increasing ear number per unit area. But too high density caused lessened grain number per spike and grain weight, and increasing bald tip length. Consistent with previous research results (Cox 1996, Rossini et al. 2011, Testa et al. 2016), the maize yield would reduce when the increase of spike per unit area could not make up for the decrease of grains per spike and grain weight as the density increased to a certain extent.

The planting density to achieve a high yield of maize was relatively broad, and the density for maximum yield in different maize planting areas was related to climate, soil, and yield potential (Wang et al. 2012). The optimal planting density of both cultivars was 7.5 × 10^4 plants/ha in this study, which was in line with some results, but also different from other studies (Li et al. 2015, Ren et al. 2017). Further increase in planting density did not improve maize yield, but low N application lowered the bald tip length, increased the spike length and grain per row, and enhanced the yield under high planting density. In the present study, the maize yield of 12 t/ha under the condition of densification was a relatively high level in the North China Plain, China (Zhao et al. 2018). To further improve the yield through planting density, it was necessary to improve the light and temperature resources, soil fertility, irrigation conditions, and other yield-limiting factors.

Although the suitable planting density and N fertiliser were 7.5 × 10^4 plant/ha and N180 for two cultivars, there were differences in the response of different density-resistant cultivars to densification and fertilisation. The lodging rate of ZD909 was lower than WK702, showing density-tolerance to some extent. Under high planting density, N180 decreased the lodging rate mainly by reducing the plant and spike height for WK702, while by reducing spike height and thickening maize stem for ZD909. Moreover, the yield decreased greatly for WK702 but did not change much for ZD909 under the density of 7.5 × 10^4 plant/ha compared with 9.0 × 10^4 plant/ha at the

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same N fertiliser rate. Under the high density of 9.0 × 10^4 plant/ha, the yield increase of N180 compared with N360 was more obvious for Weike 702 than ZD909. All these meant that ZD909 was more sensitive to high density and N application than WK702.

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