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Optimising the root traits of summer maize to improve nutrient uptake and utilisation through rational application of urea ammonium nitrate solution

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Abstract: The production of summer maize is greatly affected by nitrogen (N) sources through regulating root growth and distribution. Four N treatments in the field experiment were designed as UAN (urea ammonium nitrate solution was applied under traditional side-dressing method), urea (urea was applied under traditional side-dressing method), UWFI (UAN was applied underwater and fertiliser integration technology) and CK (no N applied). The results showed that the root length density, surface area density and volume of DH605 (mid-late hybrid) and DH518 (mid-early hybrid) under UWFI were higher than other treatments, especially in shallow layers. The root absorption area of each soil layer under N application treatments varied with the growth stage. The grain yield and the accumulations of N, P and K in the shoots showed the trend of UWFI > UAN > urea > CK. Compared with UAN and urea, the nitrogen agronomic efficiency of UWFI treatment increased by 40.5~78.6%, and the nitrogen partial factor productivity increased by 4.75~7.61%. Consequently, rational application of UAN would improve root traits, nutrient uptake and utilisation, and yield of summer maize.

Keywords: *Zea mays* L.; nitrogen fertiliser type; application method; root system; nitrogen efficiency

The root is an essential organ for maize whose traits, distribution and physiological capacity in the soil directly affect nutrients and water uptake, the development of above-ground plants, and the formation of grain yield and quality (Rasmussen et al. 2015, Feng et al. 2019). In particular, root morphological characteristics such as root length, weight, volume and absorption area play an important role in the uptake and utilisation of nitrogen (N), phosphorus (P), potassium (K) and other nutrients (Yu et al. 2014, Lynch 2019).

Root traits of crops are easily affected by soil conditions. Crops would enhance their ability to capture soil nutrients by changing root traits and make the greatest response to nutrient supply (Lynch 2011). Agronomic practices such as N application may affect the growth, distribution and function of the roots (Gastal and Lemaire 2002). Reasonable N supply would increase root dry weight, root length density and root vitality, while excessive N would not increase root growth (Haberle et al. 2006). Root traits are also altered by different forms of N. For example, applying a certain amount of nitrate-nitrogen (NO_3^--N) would promote the growth of lateral roots, while too much ammonium nitrogen (NH_4^+-N) content would shorten the lateral roots and affect the physiological functions of the roots (Schortemeyer et al. 1993, Huang et al. 2017).

The traditional agricultural N source is mainly urea, which usually has problems of high applica-

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Table 1. Chemical soil properties

Year	Soil layer (cm)	SOC	TN	NN	AN	AP	AK
		(g/kg)		(mg/kg)			
2019	0–20	7.31	2.17	32.16	5.23	72.25	180.03
	20–40	3.94	2.07	24.57	4.27	48.95	122.44
	40–60	3.30	1.88	14.32	3.39	24.50	95.27
2020	0–20	8.64	3.08	33.91	5.69	67.08	162.44
	20–40	5.22	1.63	27.92	4.03	24.60	72.83
	40–60	2.90	1.04	14.99	3.33	16.19	66.35

SOC – soil organic carbon; TN – total nitrogen; NN – nitrate nitrogen; AN – ammonium nitrogen; AP – available phosphorus; AK – available potassium

tion rate and low N use efficiency (NUE) (Liu et al. 2018). It has been estimated that as much as 40% of the fertiliser used in the United States is liquid N fertiliser, and urea ammonium nitrate solution (UAN) accounts for 80% of liquid fertiliser (Nikolajsen et al. 2020). UAN is a N source that integrates NO_3^--N, NH_4^+-N and amide N. Reasonable application of UAN would save at least 30 kg/ha of fertiliser than urea (Sundaram et al. 2019). However, it is not widespread in China where an increase in crop yield during its application has been reported (Wang et al. 2018). This study was to explore how UAN and urea affect root traits, nutrient uptake, NUE and grain yield of summer maize under different N application methods.

MATERIAL AND METHODS

Study site. The field experiment was carried out at Mazhuang research field (35°99'N, 117°01'E, 91 m a.s.l.), Shandong province, China in maize growth seasons of 2019 and 2020. This region is characterised by brown loam soils (U.S. Classification: Typic Paleustalfs) and a temperate continental monsoon climate. The basic nutrient content of the 0–60 cm soil layer is listed in Table 1 and meteorological conditions are shown in Figure 1.

Experimental design. The treatments consisted of one control treatment without N fertiliser (CK) and two fertilisation methods. (I) urea (46% pure N) and urea ammonium nitrate solution (UAN, 32% pure N) were applied under the traditional side-dressing method. Both of them were applied in bands near the plant row incorporated into the soil *via* ploughing and the depth was 5 cm. (II) UAN was applied underwater and fertiliser integration technology (UWFI). The micro-sprinkling hose was installed between maize rows and water (equivalent to 10 mm precipitation) was used to feed UAN into the pipeline for spraying. In the six-leaf stage (V6) and the twelve-leaf stage (V12), N fertiliser was applied at a ratio of 4:6, and the amount was 210 kg N/ha. Each treatment was repeated 3 times, and the plot area was

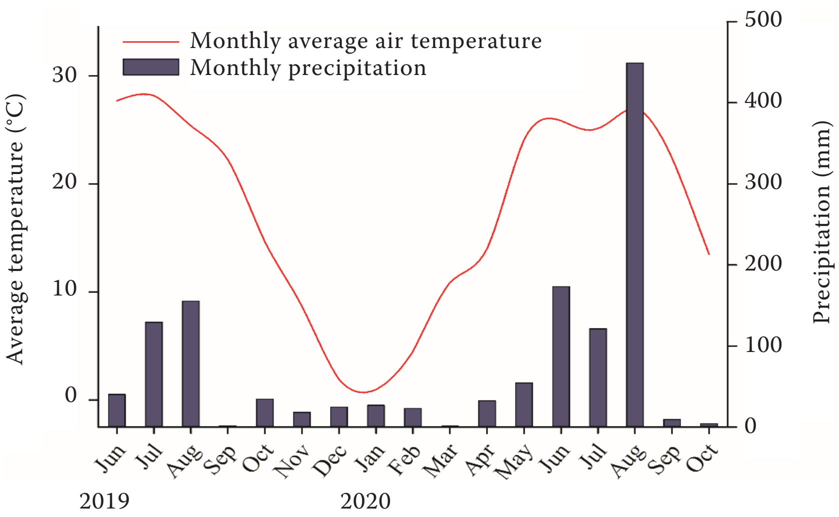

Figure 1. Rainfall conditions during the 2019–2020 growing seasons

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9.6 × 34.7 m. DH605 and DH518 were sown separately at a density of 75 000 plants/ha in early June from 2019 to 2020. DH605 (mid-late hybrid) and DH518 (mid-early hybrid) have different growth periods, which are widely represented. Before summer maize planting, 23.1 kg P/ha and 56.0 kg K/ha were applied.

Sampling and measuring. The roots were sampled at the twelve-leaf stage (V12), tasseling stage (VT), milk stage (R3) and maturity stage (R6) in 2019 and 2020 growing seasons. Three plant roots were sampled per plot by extracting them from a total soil volume of 50 cm length × 20 cm width × 60 cm depth with three separated soil layers. The methylene blue dyeing method was used to determine the total absorption area and active absorption area of the fresh root sample. Roots were dipped into a series of three beakers filled with methylene blue solution for 1.5 min. Then the solution volumes (V_1, V_2, and V_3) of three beakers were measured, and the absorbance of methylene blue solution (diluted 10 times) was recorded at 660 nm using an ultraviolet spectrophotometer (UV-2450, Shimadzu, Japan). The concentrations (C'_1, C'_2, and C'_3) of the methylene blue solution were calculated using a standard curve. Lastly, the root sample images were captured using the Epson Perfection^{TM} V800 scanner (Beijing, China) and analysed with the software Win RHIZO (Québec, Canada).

Three maize plant samples were obtained from the centre of each plot at the V12, VT, R3 and R6 stages. All samples were separated into stalks and leaves at harvest, placed in an oven at 105 °C for degreening and then dried at 80 °C to a constant weight. After the samples were dried and crushed, they were digested with the H_2SO_4-H_2O_2 method, the total N and P content of the samples were measured with the AA3 continuous flow analyser, and the content of K was measured with the FPT 640 flame photometer (Shanghai, China). At R6, 30 consecutive plants per row were harvested as replication and used to measure yield.

Calculation. Root length density (RLD, cm/cm^3), root surface area density (RSAD, cm^2/cm^3), total absorption area (TAA, m^2/plant), active absorption area (AAA, m^2/plant), N (P, K) accumulations (AC, kg/ha), N agronomic efficiency (AE_N, kg/kg) and N partial factor productivity (PEP_N, kg/kg) were calculated by using the following formula:

$$TAA = [(C - C'_1) \times V_1] \times 1.1 + [(C - C'_2) \times V_2] \times 1.1 \quad (1)$$

$$AAA = [(C - C'_3) \times V_3] \times 1.1 \quad (2)$$

$$RLD = L/V \quad (3)$$

$$RSAD = S/V \quad (4)$$

$$AC = DM \times PC \quad (5)$$

$$AE_N = (YF - YC)/NA \quad (6)$$

$$PEP_N = YF/NA \quad (7)$$

where: C – original solution concentration (mg/mL); C' – leaching solution concentration (mg/mL); V_1, V_2, and V_3 – solution volume (mL); L – root length (cm); V – volume of the soil sample (cm^3); S – root surface (cm^2); DM – dry matter (kg/ha); PC – plant N (P, K) content (%); YF – grain yield (kg) in the fertilised plots; YC – grain yield (kg) in the control plot; NA – amount of applied N (kg).

Statistical analysis. Excel (Redmond, USA) was used to collect data and calculate the standard deviations. The statistical analyses were conducted using SPSS 21.0 (SPSS Inc., Chicago, USA). All data were subjected to one-way analyses of variance (ANOVA) followed by mean comparisons using Duncan's multiple range test ($P \leq 0.05$). Effect of fertilisation treatment was evaluated separately within each year, hybrid, stage and soil layer. The Pearson correlation analysis was used for the relationships between grain yield and root traits. Figures were produced with Sigma Plot 14.0 (Systat Software Inc., San Jose, USA) and Graphpad Prism 9.0 (GraphPad Software Inc., San Diego, USA).

RESULTS

Root length density, surface area density and volume. The root length density at VT showed a trend of UWFI > UAN > urea > CK, while there was no difference between UAN and urea treatment in 2020 (Figure 2). Compared with CK, urea and UAN, the average RLD of UWFI increased by 32.0, 15.6 and 8.7%, respectively, while there was no significant difference among the three N treatments at R3. Although there was no significant difference in root surface area density at the VT stage among the three N treatments in 2019, the UWFI treatment in 2020 increased significantly. Furthermore, the difference between UAN and UWFI was not significant, but both of them were higher than urea and CK at the R3 stage. The root volume (RV) was greater under three N treatments relative to the control treatment. However, there was no significant difference in RV between UAN and UWFI treatment. The results of the roots in each soil layer at different growth stages also illustrated the UWFI of the two hybrids showed greater RLD, RSAD and RV, compared with other treatments. The results were basically in agreement and showed similar trends in both hybrids (Table 2).

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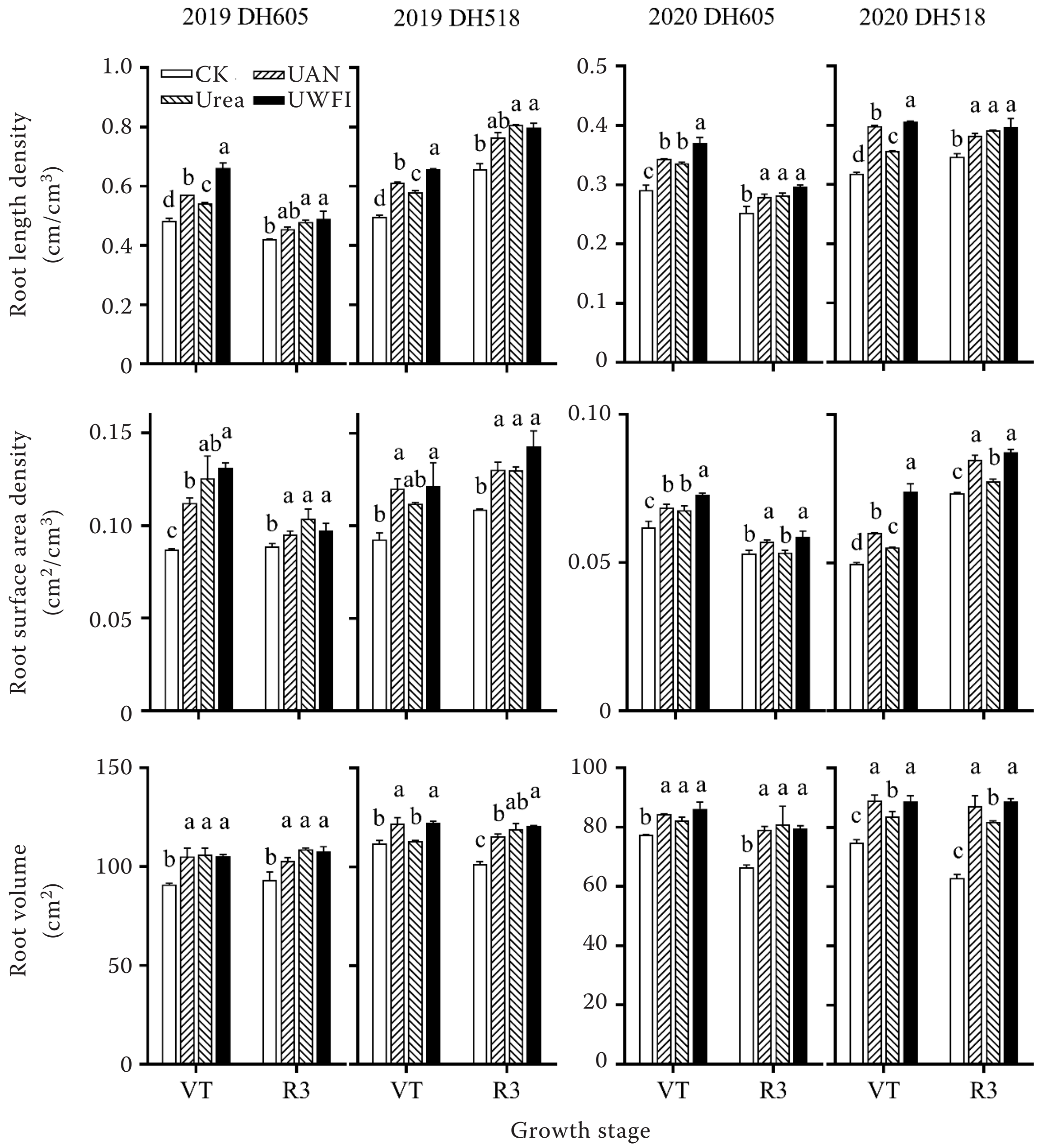

Figure 2. Effects of different fertilisation treatments on total root length density, root surface area and root volume of summer maize. CK – no N applied; Urea – urea was applied under the traditional side-dressing method; UAN – urea ammonium nitrate solution was applied under the traditional side-dressing method; UWFI – UAN was applied underwater and fertiliser integration technology. Different letters indicate significant differences at $P < 0.05$. Error bars represent the standard error of the mean; VT – tasseling stage; R3 – milk stage

Root absorption area. N application affected the root absorption area in each soil layer at different stages. The root absorption area of urea at the V12 stage was significantly higher than other treatments in the 0–20 cm soil layer. However, the root absorption area of UAN and UWFI treatments increased significantly and the increase was much greater than that of urea treatment after V12. In the 20–40 cm soil layer, the urea treatment provided greater total absorption area and active absorption area in DH605 compared to the other treatments at V12 (the opposite trend was shown in DH518). Obviously, the UWFI treatment exhibited larger TAA and AAA in the deep soil layer (40–60 cm) at V12 and VT stage, while the urea treatment was significantly lower than the other treatments. However, there was no significant difference at the R3 stage among the three N treatments (Table 3).

The accumulations of nitrogen, phosphorus, and potassium. The accumulations of N, P, and K in the

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Table 2. Effects of different fertilisation treatments on root length density, surface area density and volume of summer maize

Soil layer (cm)	Treatment	Root length density (mm/cm^3)				Root surface area density (mm^2/cm^3)				Root volume (cm^3)			
		V12	VT	R3	R6	V12	VT	R3	R6	V12	VT	R3	R6
DH605													
0–20	CK	6.60^{a}	11.49^{c}	6.82^{b}	3.50^{b}	10.40^{b}	19.58^{b}	17.57^{ab}	8.48^{ab}	28.11^{b}	70.45^{c}	70.42^{b}	32.88^{b}
	UAN	9.49^{a}	13.61^{ab}	7.33^{ab}	3.25^{b}	18.95^{a}	21.47^{b}	15.23^{b}	9.01^{ab}	43.38^{a}	84.21^{a}	79.93^{a}	58.06^{a}
	urea	8.63^{a}	12.39^{bc}	7.70^{ab}	3.24^{b}	16.95^{a}	29.81^{a}	19.17^{a}	7.70^{b}	44.99^{a}	80.12^{b}	77.42^{a}	60.36^{a}
	UWFI	8.81^{a}	15.10^{a}	7.94^{a}	4.36^{a}	12.97^{b}	29.07^{a}	19.00^{a}	9.86^{a}	41.94^{a}	84.32^{a}	81.04^{a}	60.24^{a}
20–40	CK	2.63^{a}	2.80^{b}	2.74^{b}	1.77^{b}	4.68^{a}	4.57^{c}	5.11^{a}	7.76^{b}	13.87^{a}	15.17^{b}	12.62^{ab}	8.42^{a}
	UAN	2.01^{a}	2.43^{b}	3.68^{a}	1.90^{ab}	3.46^{b}	4.74^{bc}	5.22^{a}	3.41^{a}	11.11^{a}	15.20^{b}	12.57^{b}	8.10^{a}
	urea	2.34^{a}	2.89^{b}	3.85^{a}	1.60^{b}	4.65^{a}	5.72^{b}	6.63^{a}	2.36^{c}	15.09^{a}	19.00^{a}	17.12^{a}	8.14^{a}
	UWFI	2.98^{a}	3.56^{a}	3.52^{a}	2.42^{a}	5.00^{a}	7.72^{a}	5.57^{a}	3.34^{a}	13.99^{a}	15.28^{b}	14.68^{ab}	7.36^{a}
40–60	CK	1.22^{a}	1.24^{a}	3.08^{ab}	2.64^{a}	2.01^{a}	1.91^{b}	3.89^{b}	4.16^{a}	4.85^{a}	5.35^{a}	10.24^{b}	7.59^{a}
	UAN	1.02^{ab}	1.08^{bc}	2.65^{b}	2.66^{a}	2.41^{a}	2.44^{a}	4.46^{ab}	3.96^{a}	5.23^{a}	5.64^{a}	10.47^{b}	7.56^{a}
	urea	0.89^{b}	0.99^{c}	2.83^{ab}	2.04^{ab}	2.12^{a}	2.29^{a}	5.27^{a}	2.52^{b}	5.19^{a}	6.97^{a}	14.12^{a}	8.02^{a}
	UWFI	1.17^{ab}	1.18^{ab}	3.25^{a}	1.92^{b}	2.64^{a}	2.57^{a}	4.63^{ab}	2.38^{b}	5.29^{a}	5.57^{a}	12.18^{b}	7.98^{a}
DH518													
0–20	CK	7.92^{b}	11.07^{c}	13.48^{b}	4.80^{b}	11.85^{b}	20.38^{b}	24.41^{b}	18.58^{b}	56.81^{b}	93.09^{b}	82.11^{c}	55.45^{b}
	UAN	9.41^{ab}	16.33^{a}	16.35^{a}	4.88^{b}	19.42^{a}	27.92^{a}	29.48^{a}	18.53^{b}	71.91^{a}	100.22^{a}	94.77^{a}	62.86^{a}
	urea	9.66^{a}	13.61^{bc}	14.50^{ab}	4.82^{b}	16.68^{a}	25.13^{ab}	26.85^{b}	15.73^{b}	72.12^{a}	81.21^{c}	89.88^{b}	53.43^{b}
	UWFI	9.33^{ab}	15.50^{ab}	15.04^{ab}	5.39^{a}	18.30^{a}	27.30^{a}	31.27^{a}	29.83^{a}	70.49^{a}	98.07^{a}	98.20^{a}	67.78^{a}
20–40	CK	2.02^{a}	2.31^{ab}	3.38^{bc}	4.31^{a}	4.48^{a}	4.80^{c}	4.58^{b}	5.69^{a}	12.06^{a}	11.61^{b}	10.40^{b}	10.25^{b}
	UAN	1.86^{a}	1.93^{b}	2.99^{c}	4.10^{a}	4.07^{a}	4.07^{d}	5.16^{b}	5.36^{ab}	12.10^{a}	13.00^{b}	11.14^{b}	11.10^{ab}
	urea	2.06^{a}	2.43^{ab}	5.99^{a}	2.98^{b}	4.69^{a}	5.23^{b}	8.15^{a}	3.92^{b}	10.47^{b}	19.38^{a}	18.43^{a}	12.42^{a}
	UWFI	2.01^{a}	2.72^{a}	5.20^{ab}	4.01^{a}	4.51^{a}	6.39^{a}	7.29^{a}	5.03^{ab}	12.19^{a}	14.43^{b}	13.05^{b}	11.53^{ab}
40–60	CK	1.23^{a}	1.51^{a}	2.83^{c}	1.86^{b}	2.39^{a}	2.56^{a}	3.62^{a}	3.05^{b}	7.46^{a}	7.17^{b}	8.91^{b}	5.46^{a}
	UAN	1.26^{a}	2.07^{a}	3.38^{bc}	2.43^{ab}	2.23^{a}	3.99^{a}	4.44^{a}	2.53^{b}	7.95^{a}	8.74^{ab}	9.42^{b}	5.55^{a}
	urea	1.13^{a}	1.92^{a}	3.41^{b}	2.41^{ab}	2.21^{a}	3.18^{a}	3.98^{a}	4.52^{a}	7.38^{a}	12.48^{a}	10.61^{a}	6.00^{a}
	UWFI	1.28^{a}	1.54^{a}	3.70^{a}	2.69^{a}	2.36^{a}	3.01^{a}	4.25^{a}	4.87^{a}	8.16^{a}	9.72^{ab}	9.52^{b}	5.97^{a}

Different letters in each column indicate significant differences between different fertilisation treatments ($P < 0.05$; Duncan's test). CK – no N applied; UAN – urea ammonium nitrate solution was applied under traditional side-dressing method; Urea – urea was applied under traditional side-dressing method; UWFI – UAN was applied underwater and fertiliser integration technology; V12 – twelve-leaf stage; VT – tasseling stage; R3 – milk stage; R6 – maturity stage

above-ground plants showed a gradual increase trend during the summer maize growing season, with no significant depth differences among hybrids (Figure 3). At V12, CK had the lowest N accumulation. The N, P accumulations of R6 were in the following order: UWFI > UAN > urea > CK. At V12 and VT, CK had the lowest P accumulation, but there was no significant difference among the three N treatments. At R3, both UAN and UWFI were significantly higher than the urea treatment. There was no significant difference in the K accumulation among three N treatments at V12 and R3. However, the K accumulation of UWFI and UAN were higher than the urea treatment at R6.

Nitrogen use efficiency. The application of UAN underwater and fertiliser integration technology significantly increased nitrogen agronomic efficiency and nitrogen partial factor productivity. However, there was no significant difference between urea and UAN under the traditional application method (UAN higher than urea treatment only occurred in DH605 for one year). Under UWFI treatment, on average, enhanced AE_N significantly, by 40.5~43.6% (UAN),

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Table 3. Effects of different fertilisation treatments on root absorption area of summer maize

Soil layer (cm)	Treatment	Absorption area (m^2/plant)				Active absorption area (m^2/plant)			
		V12	VT	R3	R6	V12	VT	R3	R6
DH605									
0–20	CK	59.23^{d}	134.30^{b}	106.40^{a}	59.06^{b}	29.23^{d}	65.13^{b}	51.90^{ab}	29.37^{b}
	UAN	70.43^{b}	173.63^{a}	97.23^{b}	88.18^{a}	35.01^{b}	86.08^{a}	49.87^{b}	43.64^{a}
	urea	75.03^{a}	154.90^{ab}	106.49^{a}	59.77^{b}	36.92^{a}	77.09^{a}	53.60^{a}	29.54^{b}
	UWFI	67.01^{c}	170.91^{a}	97.90^{b}	89.68^{a}	33.38^{c}	86.32^{a}	49.30^{b}	44.16^{a}
20–40	CK	12.91^{b}	28.13^{a}	13.50^{c}	12.03^{a}	6.37^{b}	13.68^{a}	4.93^{c}	6.10^{a}
	UAN	15.09^{b}	17.07^{b}	25.24^{b}	9.67^{b}	7.46^{b}	8.47^{b}	12.72^{b}	4.73^{b}
	urea	21.80^{a}	25.94^{a}	25.13^{b}	9.69^{b}	10.86^{a}	12.92^{a}	12.63^{b}	4.81^{b}
	UWFI	17.26^{b}	28.91^{a}	31.10^{a}	9.76^{b}	8.62^{b}	14.52^{a}	15.78^{a}	4.84^{b}
40–60	CK	7.17^{b}	9.00^{b}	16.68^{a}	9.61^{bc}	3.56^{b}	4.46^{b}	8.36^{a}	4.76^{bc}
	UAN	11.20^{a}	11.65^{a}	17.46^{a}	15.49^{a}	5.51^{a}	5.73^{a}	8.63^{a}	7.66^{a}
	urea	10.26^{a}	9.03^{b}	18.52^{a}	7.55^{c}	5.21^{a}	4.54^{b}	9.06^{a}	3.74^{c}
	UWFI	11.26^{a}	11.98^{a}	17.27^{a}	13.82^{ab}	5.57^{a}	6.19^{a}	8.63^{a}	6.89^{ab}
DH518									
0–20	CK	105.04^{c}	159.29^{b}	159.13^{b}	94.32^{c}	52.23^{b}	77.81^{b}	78.00^{b}	47.60^{b}
	UAN	116.46^{ab}	177.97^{a}	178.93^{a}	109.72^{a}	57.33^{ab}	88.26^{a}	87.59^{a}	54.06^{a}
	urea	119.64^{a}	160.83^{ab}	180.87^{a}	100.32^{b}	58.96^{a}	79.67^{b}	90.11^{a}	50.34^{b}
	UWFI	107.55^{bc}	176.95^{a}	178.10^{a}	108.15^{a}	53.14^{ab}	88.37^{a}	90.39^{a}	54.44^{a}
20–40	CK	32.66^{a}	24.27^{b}	17.57^{c}	19.00^{bc}	16.26^{a}	11.94^{b}	8.64^{b}	9.51^{bc}
	UAN	21.53^{bc}	26.97^{ab}	32.15^{ab}	20.31^{b}	10.66^{b}	13.34^{ab}	16.08^{a}	10.39^{b}
	urea	17.90^{c}	32.85^{a}	29.62^{b}	15.21^{c}	8.90^{b}	16.13^{a}	14.95^{a}	7.56^{c}
	UWFI	23.77^{b}	33.21^{a}	33.59^{a}	32.64^{a}	11.79^{b}	16.52^{a}	17.08^{a}	16.17^{a}
40–60	CK	15.62^{a}	10.35^{c}	18.90^{a}	5.89^{b}	7.72^{a}	5.05^{c}	9.53^{a}	2.86^{b}
	UAN	16.47^{a}	22.03^{ab}	21.19^{a}	16.03^{a}	8.14^{a}	10.91^{ab}	10.55^{a}	7.99^{a}
	urea	6.70^{b}	17.91^{b}	17.88^{a}	7.74^{b}	3.31^{b}	8.77^{b}	8.75^{a}	3.86^{b}
	UWFI	13.18^{a}	24.04^{a}	17.37^{a}	15.28^{a}	6.65^{a}	12.07^{a}	8.65^{a}	7.56^{a}

Different letters in each column indicate significant differences between different fertilisation treatments ($P < 0.05$; Duncan's test). CK – no N applied; UAN – urea ammonium nitrate solution was applied under traditional side-dressing method; Urea – urea was applied under traditional side-dressing method; UWFI – UAN was applied underwater and fertiliser integration technology; V12 – twelve-leaf stage; VT – tasseling stage; R3 – milk stage; R6 – maturity stage

65.0~78.6% (urea), respectively. Similarly, compared with UAN and urea treatment, the PFP_N of UWFI increased by 4.8~5.1% and 6.6~7.6%, respectively (Figure 4).

Grain yield. The application of UAN significantly increased the grain yield of summer maize, especially underwater and fertiliser integration technology. The results were basically in agreement and showed similar trends in both hybrids. The average grain yield of UWFI treatment was enhanced by 18.7~19.2, 4.8~5.1 and 6.6~7.6% compared with CK, UAN and urea, respectively (Figure 5).

DISCUSSION

The root is the main organ of maize for nutrient uptake, water and material transportation, and its characteristics and functions play an important role in regulating resource utilisation and forming yield (Guan et al. 2014). Under suitable water conditions, N application could promote root growth (Zhang et al. 2019). In this study, different N sources and application methods had significant effects on root traits such as root length density, surface area density, and volume of summer maize and the changing trends of the two hy-

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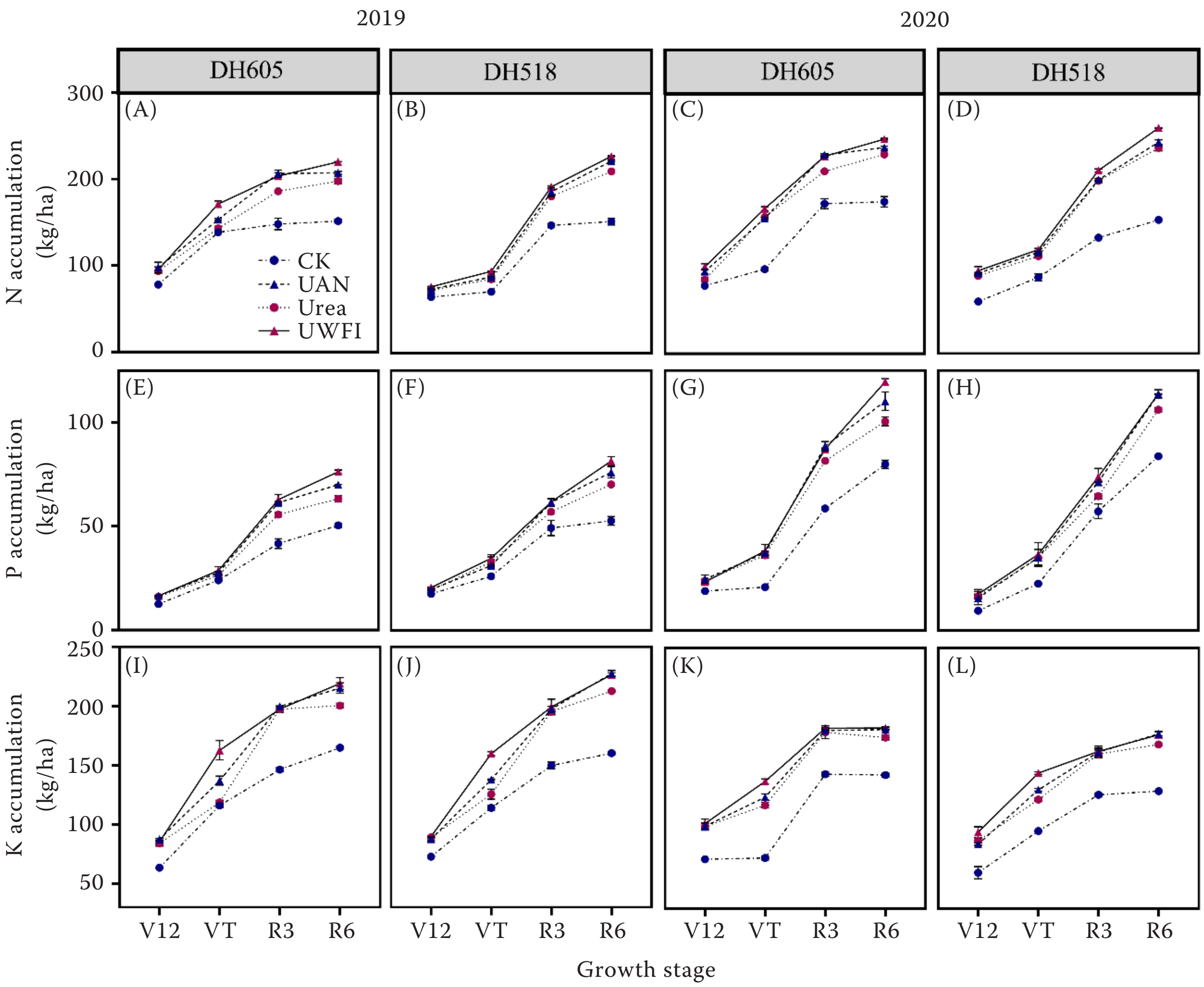

Figure 3. Effects of different fertilisation treatments on nitrogen, phosphorus and potassium accumulations of summer maize. V12 – twelve-leaf stage; VT – tasseling stage; R3 – milk stage; R6 – maturity stage

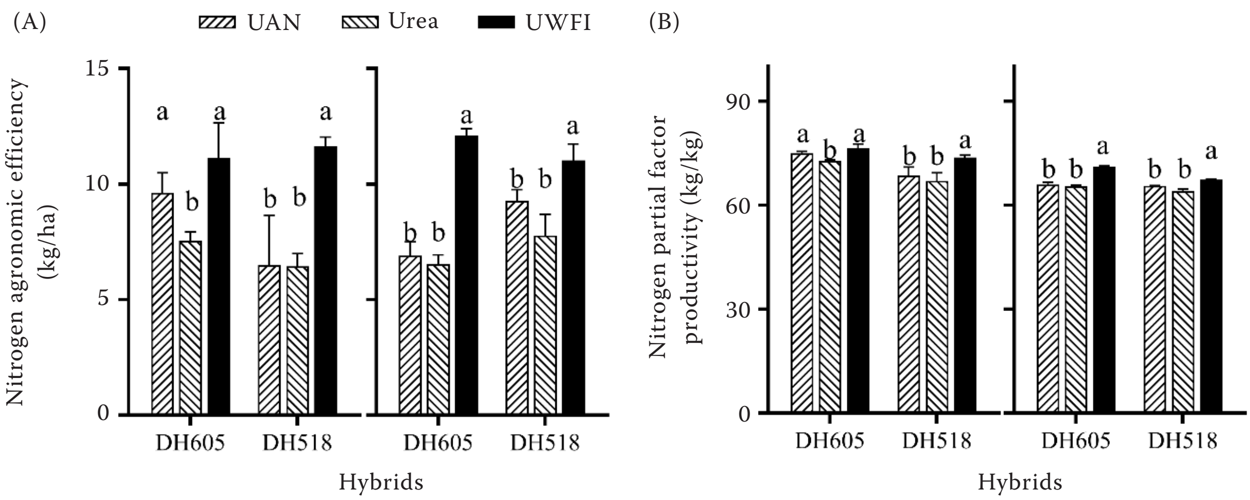

Figure 4. Effects of different fertilisation treatments on nitrogen efficiencies of summer maize in (A) 2019 and (B) 2020. Different letters indicate significant differences at $P < 0.05$. UAN – urea ammonium nitrate solution was applied under traditional side-dressing method; Urea – urea was applied under traditional side-dressing method; UWFI – UAN was applied underwater and fertiliser integration technology

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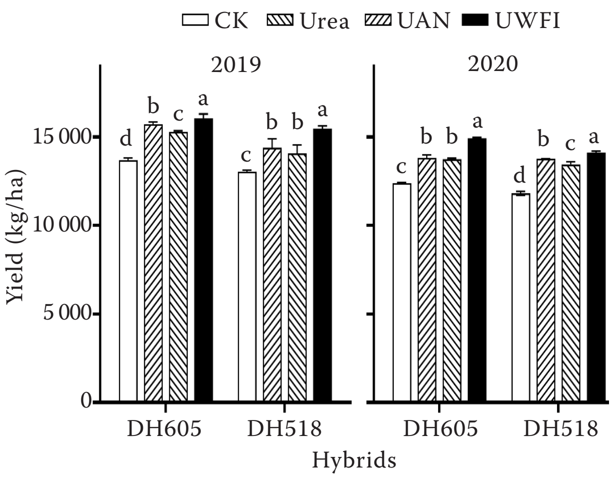

Figure 5. Effects of different fertilisation treatments on grain yield of summer maize. CK – no N applied; Urea – urea was applied under traditional side-dressing method; UAN – urea ammonium nitrate solution was applied under traditional side-dressing method; UWFI – UAN was applied underwater and fertiliser integration technology

brids were similar (Figure 2). Compared with urea, the root length density and volume of UAN increased significantly, especially in shallow soil (0–20 cm) (Table 2). Obviously, the N source had a significant regulatory effect on the root traits. The main difference between UAN and urea was the form of N, and the application of UAN significantly prolonged the residual time of available N in the soil and reduced the loss of N (Ren et al. 2021). Trapeznikov et al. (2003) reported that a large number of roots proliferate in the nutrient-rich area, through a series of changes such as root elongation and lateral root branching in response to the local supply of nutrients to improve nutrient uptake capacity.

The results of root length density, surface area density and volume showed that UWFI were higher than other treatments, which also indicated that the application method of UAN affected the root traits (Figure 2). Under the traditional side-dressing method, part of the root grows and absorbs in

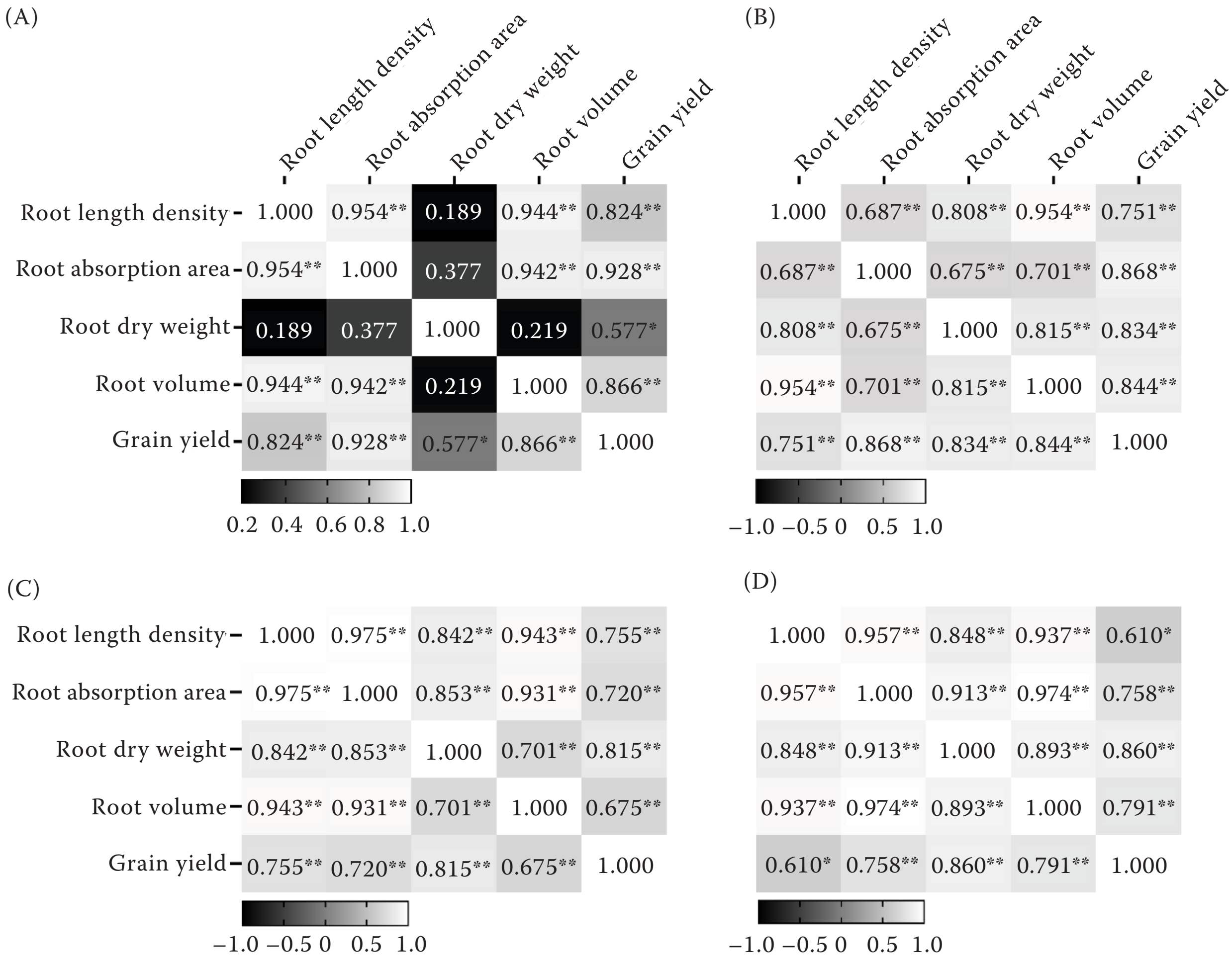

Figure 6. Correlations between root traits and grain yield of DH605 and DH518 at VT (tasseling stage) (A, C) and R3 (maturity stage) (B, D). *$P < 0.05$; **$P < 0.01$

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a N-rich place after being exposed to N (Cheng et al. 2022). However, N fertiliser is evenly dispersed in the shallow layer of the soil under the water and fertiliser integration technology, increasing the effective contact area of the roots with N. In addition, increasing the root absorption area and active absorption area was conducive to increasing the effective area of root contact with the soil and the ability to transport nutrients to the above-ground plant parts (Liu et al. 2017). After the application of UAN (V12), the root absorption area and active absorption area rapidly expanded to improve the nutrient capture ability, which also explained the reason for the increase in root length density (Table 3). Chevalier and Schrader (1977) reported that the physiological activity of the root and its affinity for nitrate play an important role in the absorption of N. Most of the urea was transformed into suitable N forms absorbed by maize, thus delaying the expansion of the root absorption area and active absorption area. The deep root system is considered an ideal way to capture downwardly moving nitrates. Compared with the UAN treatment, the UWFI increased the root length density and absorption area in the deep layer (20–60 cm). The reason for this may be that the content or dispersion of nitrate moved into the deep soil increased, which affected the characteristics and physiological activity of the deep roots.

The results also showed that the accumulations of N and K at VT were expressed as: UWFI > UAN > urea > CK (Figure 3). The UWFI at R3 and R6 also showed higher accumulations of N, P, and K. Strong nutrient absorption ability and sufficient nutrient supply during the growth stage are the key to the high yield of maize (Habibullah et al. 2017). The results of grain yield showed that UWFI treatment was significantly higher than UAN and urea as well (Figure 5). At the same time, nitrogen agronomic efficiency and nitrogen partial factor productivity obtained by UWFI treatment were significantly higher than those of UAN and urea (Figure 4). Correlation analysis showed that the root length density, absorption area, dry weight, volume and grain yield of DH605 and DH518 significantly positively correlated at VT and R3 (Figure 6). These also showed that the root traits affected by different fertilisation treatments were important factors for the increase in grain yield.

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