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Sustainable controlled-release urea placement depth reduces lodging risk and enhances spring maize productivity

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Abstract: Deep placement of controlled-release urea is an effective fertiliser management strategy for improving the maize productivity, but it is not clear whether and how controlled-release urea depth affects the stem and root lodging of spring maize. Two consecutive years of field experiments were conducted to elucidate stem and root lodging properties and their relationship between grain yield and lodging behaviours under various controlled-release urea placement depths. Results depicted that compared to broadcast nitrogen treatment (D0), deep controlled-release urea significantly decreased the stem lodging rate by 34.7–80.4%, which contributed to improving the mechanical characteristics of the internode by optimising the internode diameter and dry matter in the third basal internode as well as higher lignin content. In addition, due to a greater and deeper root system (root dry weight, root surface area, root length and root width) as well as larger angle, diameter, and tension of aerial root that significantly decreased root lodging rate (37.0–88.4%). Furthermore, deep placement of controlled-release urea significantly increased the 100-grain weight, grain number and harvested index by constructing a deeper and larger root system, which significantly improved maize grain yield by 14.2–38.5%, and the nitrogen use efficiency increased by 4.8–10.7%. The highest grain yield, nitrogen use efficiency and lowest lodging rate occurred in controlled-release urea placement depths of 15 cm. Hence, our study suggests that controlled-release urea placement depths of 15 cm were an efficient nitrogen fertiliser management strategy to improve crop productivity as well as lodging resistance in spring maize.

Keywords: slow-release fertiliser; environmental condition; deep fertilisation; *Zea mays* L.

In conventional maize planting systems, farmers' fertiliser is artificially urea surface broadcasting method, which can lead to uneven fertiliser placement accompanied by crop lodging, especially in the case of excessive nitrogen application (Li et al. 2023, Zhang et al. 2022, 2023). Controlled-release urea is widely used in rice, wheat and maize (Qiang et al. 2020, Zhu et al. 2020, Zhang et al. 2023, Lan et al. 2024). The controlled-release urea placement depths significantly impact nitrogen use efficiency, which greatly improves crop yield and reduces nitrogen loss (Ke et al. 2018). Previous reports have shown deep controlled-release urea placement (12 cm) could reduce the nitrogen addition by 20% and improve nitrogen use efficiency, resulting in yield benefits (Qiang et al. 2022, Hu et al. 2023). Chen et al. (2023) and Wu et al. (2022) found that deep nitrogen fertilisation can improve crop yield by promoting root

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growth and leaf photosynthetic characteristics. Deep nitrogen fertilisation can reduce fertiliser application rate while maintaining even increasing grain yield (Hu et al. 2023). However, controlled-release urea was affected by environmental conditions (Wu et al. 2021), so it is essential to adopt suitable fertilisation depths to exert the high efficiency of controlled-release urea.

It is well known that maize production increases with improved planting density and fertiliser application rate, while lodging risk is ignored under high-yielding conditions (Novacek et al. 2013, Zhang et al. 2023). High yields often exhibit high lodging risks while increasing the production cost (Xu et al. 2018, Zhang et al. 2023). Studies (Li et al. 2015) reported that root and stem lodging could result in 14% and 28% loss rates of yield at the maize jointing stage and could result in 30–38% and 45–48% loss rates of yield at the maize grain filling stage, respectively. Therefore, lodging has become a bottleneck problem restricting yield improvement and mechanical harvest. In the eastern Hebei Province, rainfall is concentrated in July and August (in the critical period of maize anthesis and grain filling); maize lodging was often affected by rainfall and other adverse climatic conditions, so maize lodging has become one of the important reasons restricting further increase in densely planted maize output in this area. It is customary to believe that stem lodging is more prevalent in the field, but root lodging is also responsible for at least 20% of maize production (Jia et al. 2018). Stem break at or below the ear segment is called stem lodging; root lodging is a certain angle when the stalk is more than 30° from the vertical line, and the stem does not break (Novacek et al. 2013, Bian et al. 2016). Keeping the plant upright requires stronger root support and stem strength. Maize population morphological, the third basal internode morphological, mechanical and chemical properties of the stem play important roles in resistance to stem lodging (Berry et al. 2021, Ahmad et al. 2023). Also, the lodging resistance of crop plants has been shown to be closely related to the root system; the main reason for root lodging is the failure of the root-soil anchoring system. The root's morphology and distribution in the soil, such as root depth and width, all affect the pull resistance of plants and root lodging. Pellerin et al. (1990) found that the breaking point of the lodging plant is at the adventitious root of the higher internode, and the mechanical strength of the aerial root (brace root) in the higher internode plays an important role in stem stability. Qian et al. (2024) found that straw addition could enhance the root-pulling force by optimising root growth and deepening root distribution. Li et al. (2023) have shown that higher root biomass accumulation was a necessary condition to improve root lodging. Researchers have recently attempted to improve crop lodging resistance through agronomic strategies such as nitrogen management, plant growth regulators and planting strategy (Kamran et al. 2018, Li and Li 2021, Ahmad et al. 2023, Liu et al. 2023). Meanwhile, Li et al. (2023) verified that deep nitrogen fertilisation was an effective agricultural practice which could simultaneously improve rice's crop production and lodging resistance.

According to the existing literature reports, how to improve maize lodging resistance becomes an urgent problem to be solved. Therefore, it is crucial to further study lodging resistance characteristics and its regulation of maize production to improve the lodging resistance ability of the high-yielding maize population. It was reported that compared with surface broadcast fertilisation, deep fertilisation improved maize root distribution and enhanced root support strength (Wu et al. 2022), which may help to reduce the risk of stem and root lodging. However, controlled-release urea placement depths on maize lodging have never been studied so far. Moreover, previous studies focused on stem lodging, while root lodging was very limited. Therefore, we hypothesise that deep placement of controlled-release urea could reduce the risk of plant lodging compared to surface broadcasting, which could also modify the crop morphological traits and improve root development and morphology. Field trials were conducted in North China for two consecutive years, from 2022 to 2023. The objectives of our study were to (1) comprehensively analyse stem and root lodging as well as grain yield as influenced by controlled-release urea placement depths; (2) investigate population characteristics, stem characteristics and root characteristics under deep controlled-release urea and determine their relationships with lodging. These results can provide a powerful scientific basis for the enrichment of maize cultivation theory of lodging resistance and provide a theoretical basis for optimising nitrogen management to regulate stem traits and root development.

MATERIAL AND METHODS

Experimental field conditions. Field trials were conducted from 2022 to 2023 at Luanzhou, Hebei

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Province, China (39.7N, 118.7E). The annual average temperature is 11.8 °C, the precipitation is 527 mm, and the annual sunshine is 2 720 h. The total precipitation for the 2022 and 2023 growing seasons were 488 mm and 598 mm, respectively (Figure 1). The soil type of the test site was sandy loam (classified as Typic-Hapli-Udic Argosols according to the Chinese Soil Taxonomy (CRGCST 2001)). The initial chemical properties of the 0–20 cm soil layer measured in 2022 are as follows: organic carbon was 15.35 g/kg, alkali-hydrolysed nitrogen content was 2.0 g/kg, available phosphorus content was 36 mg/kg, and available potassium content was 130 mg/kg, and pH_{H_2O} was 7.2.

Soil organic carbon was measured using the potassium dichromate external heating method. The alkali-hydrolysed nitrogen content analyses using an AA3-A001-02E Auto-analyser (Bran-Luebbe, Norderstedt, Germany), the potassium was determined by the Egner-Riehm method, and phosphorus by the Olsen method. pH was measured by reading using a pH meter (Hu et al. 2019).

Experimental design. In both years, the field trials were conducted, and a randomised block design with three replications was adopted, which consisted of six treatments: N0 – non-addition nitrogen fertilisation; D0 – surface broadcasting NPK fertiliser and four NPK fertilisers placed at different depths below the soil surface, recorded as 5 cm (D5), 10 cm (D10), 15 cm (D15) and 20 cm (D20). An identical amount of fertiliser was applied in D0, D5, D10, D15, and D20 treatments. The applied mineral fertilisers were N (30% N (controlled-release urea, N 15%) + 70% N (normal urea, N 46%), 240 kg N/ha), P (calcium superphosphate, 17.6% P, 66 kg P/ha) and K (potassium fertiliser, 41.5% K, 62 kg K/ha). Controlled-release urea, calcium superphosphate and potassium fertiliser are applied as basal fertiliser. Normal urea was applied 70% at the 10^{th}-leaf stage and 30% at the tasseling stage. Before the test, all plots of soil subsoiling operation were carried out at a depth of 40 cm, and then the rotary tillage operation was carried out to level the land. Before seeding, the fertilisation strip was formed by manual trenching; the strip depth was consistent with the fertilisation depth in the corresponding treatment, and the spacing between the fertilising furrows was 60 cm. N0 treatment uses only the same phosphate and potassium fertilisers as the other treatments. Each plot area was 70 m^2 (10 m length × 7 m width). Maize cultivar Zhengdan958, which was produced by the Institute of Grain Crops, Henan Academy of Agricultural Sciences (locally

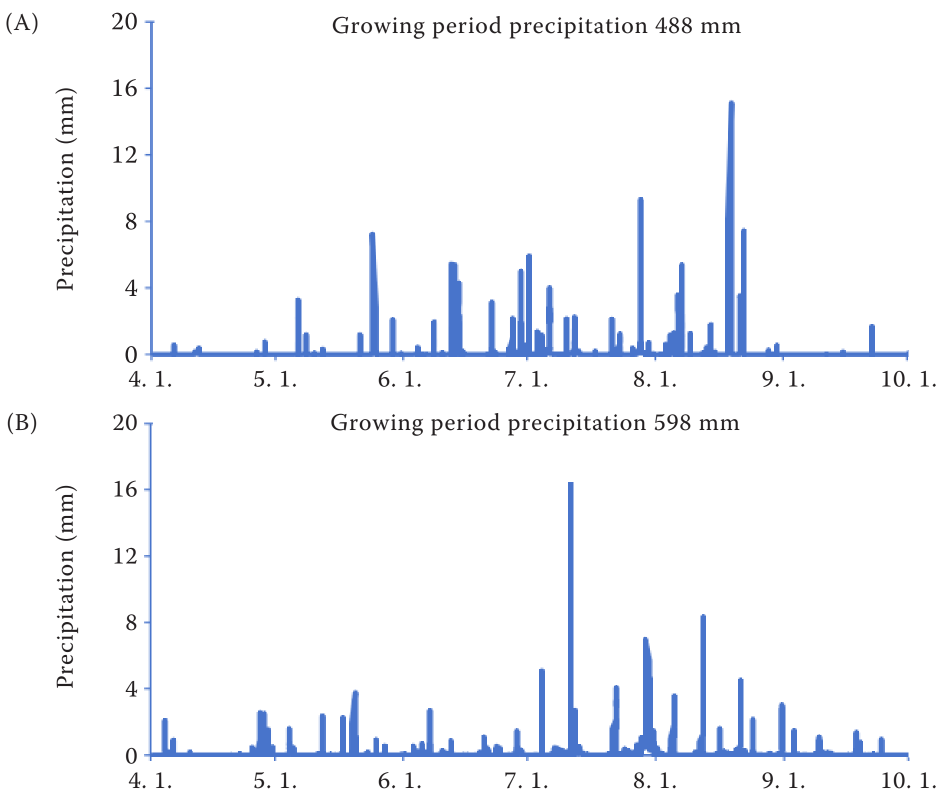

Figure 1. Precipitation in (A) 2022 and (B) 2023 spring maize growing seasons

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planted widely, stay green and lodging resistance), was selected in this experiment with a density of 90 000 plants/ha, which was sown on May 7 and April 29 and harvested on September 25 and September 20 across two years. The fields were managed in accordance with local management practices, with no irrigation throughout the growing season.

Root lodging characteristic parameters. Average tensile force of aerial root: nine representative sample plants were randomly selected in each plot, and the FGJ-10 digital dynamo-meter (Shimpo, Japan) was used to pull the air roots in the vertical direction and the force displayed on the instrument was the bending resistance of the aerial roots. The angle and diameter of aerial root: the angle between the first layer of airborne roots and stems was measured with a protractor as the angle of aerial roots. The diameter of the aerial root was determined with vernier callipers at the middle part of the first layer of soil airborne roots. Root width: nine representative sample plants were randomly selected in each plot, and the above-ground part was cut off and brought back to the laboratory. With the plant as the centre, the marks were placed at half-plant and half-row spacing, and the soil was dug down to a depth of 30 cm. The horizontal extension width of the node root at a depth of 20 cm in the soil layer was measured by a ruler and recorded as root width. Root dry matter and morphology: the underground roots were sampled using the soil profile method. The roots were excavated to a depth of 60 cm in a horizontal area with the base of the plant as the centre and a radius of 20 cm, which were divided into four layers of 0–10, 10–20, 20–40 and 40–60 cm. After sampling, the roots were washed with water and scanned with an EPSONV300 root scanner (Beijing, China). The generated images were analysed with WinRHIZO software (WinRhizo ProVision 5.0, Québec, Canada) to obtain root characteristic parameters, including root length and surface area. After scanning, the root's dry weight was recorded after drying to a constant weight in an oven at 105 °C for half an hour and then at 75 °C. All the above indices were measured at the grain-filling stage in both years.

Stem lodging characteristic parameters. Population characteristics: the plant height and centre of gravity height of fifteen complete maize plants were randomly measured in each plot. The height examined by a ruler from the base of the plant to the tip of the tassel was recorded as the plant height. The whole maize plant was placed on a fulcrum, and the stalk was moved along the fulcrum to find the equilibrium point of the plant. The distance between the stalk base and the equilibrium fulcrum was measured and recorded as the centre of gravity height of the plant. Internode diameter and dry weight: internode diameter and internode dry weight were of random fifteen maize plants were measured. The diameter of the third basal internode was measured with a vernier calliper at an accuracy of 0.001 mm, as described by Ma et al. (2014). Then, the dry weight of the third basal internode was determined after drying at 105 °C for half an hour and drying at 80 °C. Stem breaking strength (BS) and rind penetration strength (RPS): BS was recorded as the maximum force required to break the third internode, and RPS is the amount of force to puncture the stalk rind. BS and RPS as indicators of the stem mechanical strength were measured with reference to the method of Xu et al. (2017). Measurements were obtained using AWOS-SL04 Stalk Strength Tester (Hangzhou TOP Instrument, Hangzhou, China). Lignin contents: the lignin content was determined by the bromo-acetyl method, referring to the method of Fukushima et al. (2015). In the two-year experiment, natural lodging occurred mainly from grain filling to the maturity stage. Maize lodging plants were recorded from the grain-filling stage to physiological maturity in each plot. When the angle between the stem and the ground is less than 45° and the stem does not break, the plant is considered root lodging (Sezegen and Carena 2009); if the stem breaks, we classify it as stem lodging. Lodging rates = the number of plants lodged/the total number of plants in each plot (Novacek et al. 2013). The stem lodging resistance index = BS of the third basal internode/centre of gravity height (Li and Li 2021).

Maize productivity and nitrogen use efficiency. Dry matter weight, plant nitrogen accumulation: plants' dry matter weight was determined after drying it in an oven-dried at 105 °C for half an hour and then dried at 75 °C until a constant weight. The nitrogen concentration of the oven-dried plant material was determined by an automatic Kjeldahl nitrogen determination system (Kjeltec 8400, FOSS Analytical AB, Denmark, Sweden) (Li et al. 2017). Nitrogen accumulation in the plant = dry matter weight (kg) × nitrogen concentration (g/kg). The nitrogen use efficiency (NUE, kg/kg) was calculated as follows (Moll et al. 1982): NUE = grain yield (kg/ha)/plant nitrogen accumulation at maturity (kg/ha) × 100. The

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nitrogen partial efficiency (NPE, kg/kg) = grain yield (kg/ha)/nitrogen application rate (kg/ha). Grain yield and yield components: the side rows were avoided at maize maturity, and five rows of maize were harvested from each plot. The harvested ears and grain number per ear were recorded. The fresh weight of the grain was recorded before drying in an oven-dried at 75 °C until constant weight and then measured with a balance that had a precision of 0.0001 g. The grain yield was converted to a standard 13% moisture content.

Statistical analysis. Microsoft Excel software 2021 (Microsoft Corp., Washington, USA) was adopted for data. SPSS 20.0 statistical software (SPSS Inc., Chicago, USA) was adopted to perform ANOVA. Multiple comparisons of test results were performed by least-significant difference (*LSD*), with significance levels of 0.05. Origin 2023 software (OriginLab, Massachusetts, USA) was used for principal component analysis (PCA) and mapping.

RESULTS

Lodging behaviour. In both years, the stem and root lodging rates of spring maize were significantly affected by the controlled-release urea placement depths (Figure 2). Deep placement of controlled-release urea effectively decreased the stem lodging rates. In particular, the lowest stem lodging rates of 1.31% were attained under the D15 treatment, while the highest stem lodging rates of 9.94% were attained under the N0 treatment, an average of two years. The root lodging rates in 2022 and 2023 followed the order of D15 < D20 < D10 < D5 < D0 < N0. Compared to D0, the root lodging rates decreased by 85.5% and 83.3% under D15 in 2022 and 2023, respectively. The stem lodging-resistant index in the 2022 and 2023 growing seasons were 2.36–4.10 and 2.49–4.46, respectively. Stem lodging-resistant index in 2022 and 2023 followed the order of D15 > D20 > D10 > D5 > D0 >N0. In 2023, the root lodging rates were more severe than those in 2022, while the stem lodging rates were lower than those in 2022.

Population characteristics and stem characteristics. The population morphological and stem characteristics under different treatments in 2022 and 2023 are shown in Figure 3. Deep placement of controlled-release urea effectively improved plant height in the two growing seasons. The centre of gravity height under D0 was significantly higher than that under other treatments ($P < 0.05$).

The controlled-release urea placement depths affected the third basal internode morphology ($P < 0.05$) significantly. A significant improvement was observed in the diameter and dry weight of the third basal internode with deep placement of controlled-release urea (Figure 3). Compared to the D0, the diameter of the third basal internode increased by 5.5, 12.9, 18.3 and 12.7% in D5, D10, D15, and D20; the dry weight of the third basal internode increased by 7.4, 18.6, 25.7 and 19.9% in D5, D10, D15 and D20 (average of two years). Similarly, a significant improvement was observed in stem mechanical strength ($P < 0.05$) by deep placement controlled-release urea. In both years, the BS and RPS followed the order of D15 > D20 > D10 > D5 > D0 > N0. As well as the chemical properties were significantly ($P < 0.05$) affected

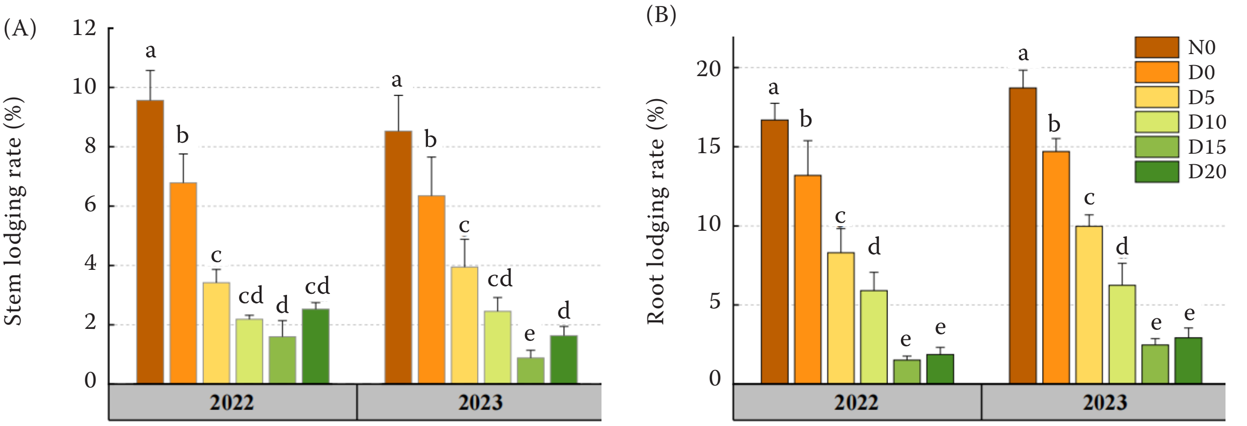

Figure 2. (A) Stem lodging and (B) root lodging of spring maize under different controlled-release urea placement depths in 2022 and 2023. Different lowercase letters indicate the significant differences among controlled-release urea placement depths at $P < 0.05$. N0 – non-addition nitrogen fertilisation; D0 – surface broadcasting NPK fertiliser and four NPK fertilisers placed at different depths below the soil surface, recorded as 5 cm (D5), 10 cm (D10), 15 cm (D15) and 20 cm (D20)

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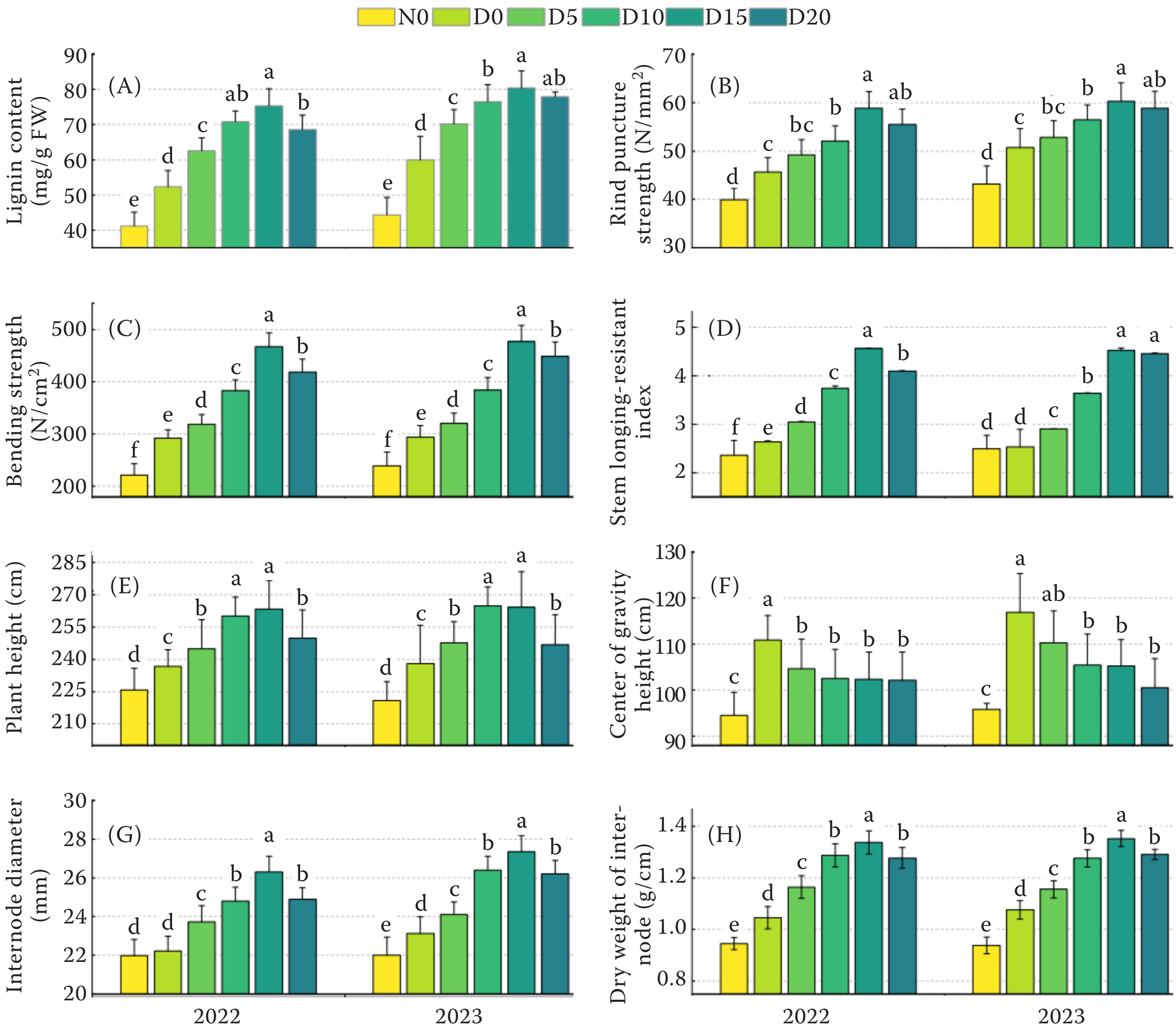

Figure 3. (A) Lignin content; (B) rind puncture strength; (C) bending strength; (D) stem lodging-resistant index; (E) plant height; (F) center of gravity height; (G) internode diameter and (H) dry weight of internode of spring maize under different controlled-release urea placement depths in 2022 and 2023. Different lowercase letters indicate the significant differences among controlled-release urea placement depths at $P < 0.05$. N0 – non-addition nitrogen fertilisation; D0 – surface broadcasting NPK fertiliser and four NPK fertilisers placed at different depths below the soil surface, recorded as 5 cm (D5), 10 cm (D10), 15 cm (D15) and 20 cm (D20); FW – fresh weight

by the controlled-release urea placement depths. The lignin content under the D15 (80.8 mg/g FW) was significantly higher than that under the D0 (56.1 mg/g FW) average of two years.

Root morphological and distribution, aerial root characters. The controlled-release urea placement depths significantly affected root morphological parameters, including root surface area, root length, root dry weight, and root width ($P < 0.05$, Figures 4 and 5). The deep placement of controlled-release urea significantly improved the root surface, length, and dry weight in all soil layers, and the trend was similar in both years. Compared to D0, the root surface, length, and dry weight under D15 were increased by 78, 76 and 134% at the 0–60 cm soil layer, respectively (average of two years). In general, root surface, length, and root dry weight in 2023 were higher than these at the 0–10, 10–20, 20–40 cm soil layer and were lower than these at the 40–60 cm soil layer in 2022, mainly due to higher rainfall in 2023 than in 2022 (Figure 1). Compared to D0, root width under D15 they were increased by 33.7% (average of two years).

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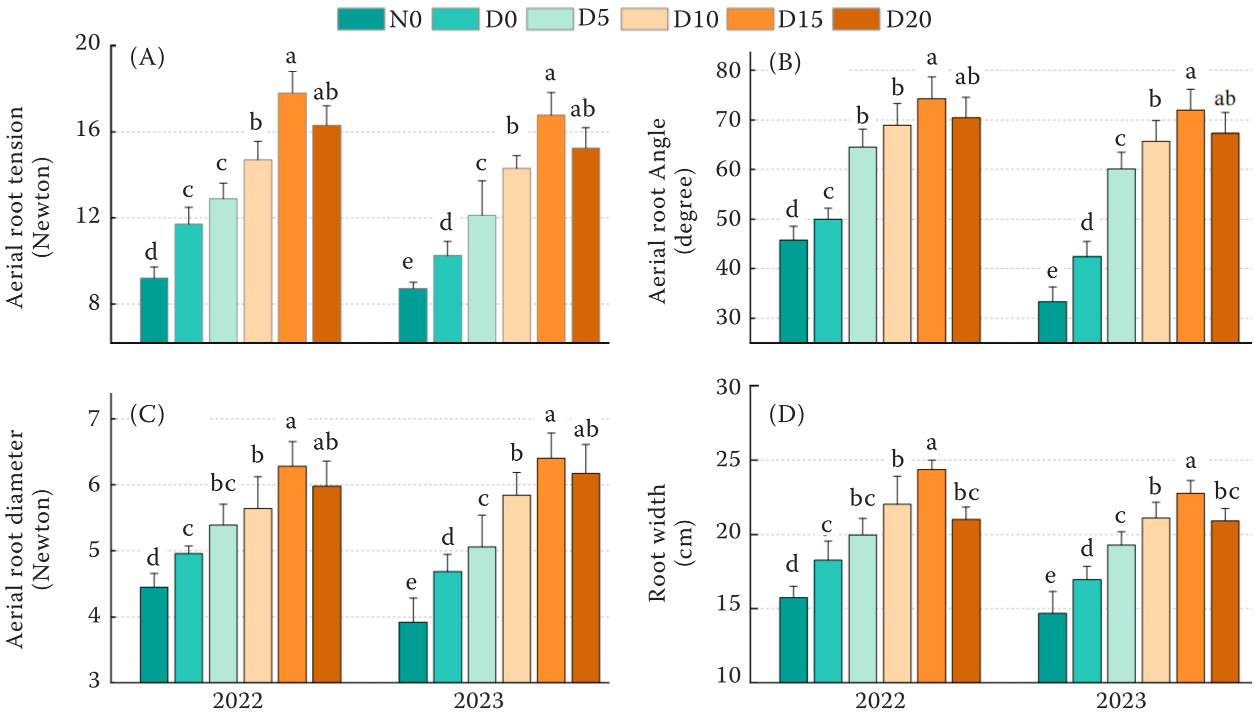

Figure 4. (A) Aerial root tension; (B) aerial root angle; (C) aerial root diameter, and (D) root width of spring maize under different controlled-release urea placement depths in 2022 and 2023. Different lowercase letters indicate the significant differences among controlled-release urea placement depths at $P < 0.05$. N0 – non-addition nitrogen fertilisation; D0 – surface broadcasting NPK fertiliser and four NPK fertilisers placed at different depths below the soil surface, recorded as 5 cm (D5), 10 cm (D10), 15 cm (D15) and 20 cm (D20)

Deep placement of controlled-release urea significantly increased the diameter, tension and angle of airborne roots in 2022 and 2023 compared to D0 treatments ($P < 0.05$). The diameter of airborne roots under deep placement of controlled-release urea was 8.4–31.7% higher than those under D0 treatments. Furthermore, the tension of airborne roots for deep placement of controlled-release urea was found to be 14.3–57.9% higher than D0 treatments. The angle of airborne roots under deep placement of controlled-release urea was 35.4–59.2% higher than D0 treatments. Overall, higher values were attained under the D15 treatment. The root width value under the D15 treatment (23.5 cm) was significantly bigger than that under the D0 treatment (17.6 cm), an average of two years.

Grain yield and yield components. Deep placement of controlled-release urea significantly affected grain yield and yield components (Table 1). Grain yields and yield components increased first and then decreased with increasing controlled-release urea placement depths. In both years, the highest yield of 11 359 kg/ha and 12 854 kg/ha were attained under the D15 treatment of 2022 and 2023, respectively. Compared to D0, the grain yields increased by 14, 31, 38 and 26% under placement depths of 5, 10, 15 and 20 cm, respectively, on average over the two years. Similarly, the maximum values of harvested ears, 100-grain weight and grain number occurred in the D15, which determined the final grain yield improvement. Generally, grain yields and yield components in 2023 were higher than those in 2022, mainly due to higher precipitation in 2023 than in 2022 (Figure 1).

Harvest index (HI), plant dry matter, plant nitrogen accumulation, nitrogen use efficiency (NUE) and nitrogen physical efficiency (NPE). Similar to grain yield, improvements were observed in the plant dry matter (5.5–24.6%) and HI (6.7–16.0%) in both years. Compared to the D0, plant dry matter increased by 5.8–21.2%, and plant nitrogen accumulation they were increased by 5.9–20.8%, on average, over the two years (Table 2). D0 obtained the lowest NUE and NPE. In both years, compared to D0, the NUE and NPE values improved by 6.3–16.6% and 14.2–38.5% on average for two years. In addition, compared to N0, the average

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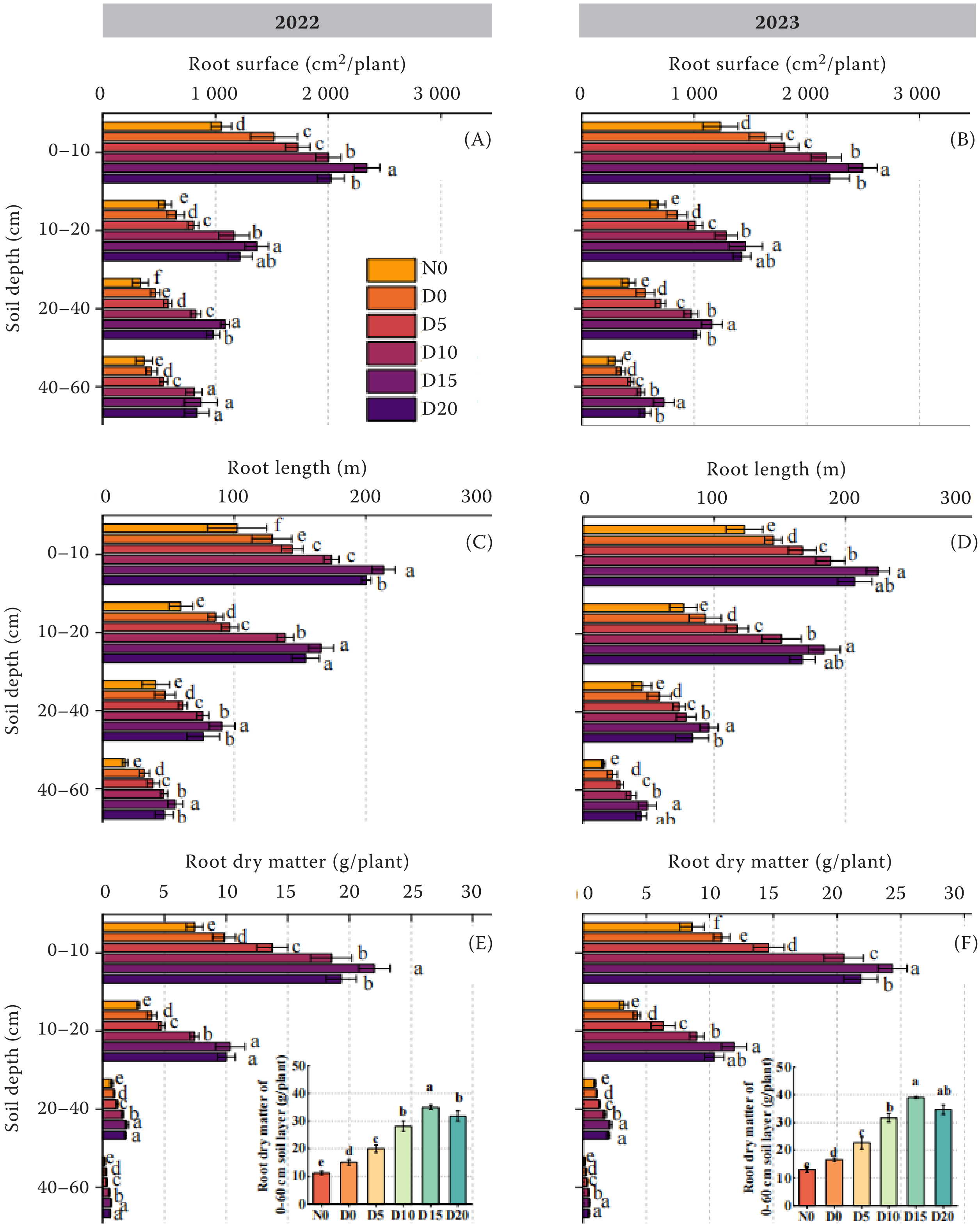

Figure 5. (A) Root surface area; (B) root length, and (C) root dry weight in 0–10, 10–20, 20–40 and 40–60 cm of spring maize under different fertilisation treatments in 2022 (A, C, E) and 2023 (B, D, F). Different lowercase letters indicate the significant differences among controlled-release urea placement depths at P < 0.05 N0 – non-addition nitrogen fertilisation; D0 – surface broadcasting NPK fertiliser and four NPK fertilisers placed at different depths below the soil surface, recorded as 5 cm (D5), 10 cm (D10), 15 cm (D15) and 20 cm (D20)

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Table 1. Grain yield and yield components of spring maize under different controlled-release urea placement depths in 2022 and 2023

Depth	Grain yield (kg/ha)		Harvested ears (ear)		100-grain weight (g)		Grain number (kernel)	
	2022	2023	2022	2023	2022	2023	2022	2023
N0	6 940^{e}	7 698^{e}	80 028^{e}	81 021^{e}	22.0^{e}	22.9^{e}	424^{d}	445^{d}
D0	79 889^{d}	8 839^{d}	82 891^{d}	83 011^{d}	24.3^{d}	26.3^{d}	467^{c}	464^{d}
D5	9 583^{c}	10 397^{c}	85 230^{c}	85 915^{c}	26.1^{c}	27.7^{c}	502^{b}	535^{c}
D10	10 651^{b}	12 436^{ab}	87 889^{b}	88 626^{b}	29.7^{b}	32.5^{b}	512^{b}	556^{b}
D15	11 399^{a}	12 854^{a}	88 686^{a}	89 440^{a}	32.2^{a}	36.0^{a}	551^{a}	637^{a}
D20	10 281^{b}	11 701^{b}	87 450^{b}	88 179^{b}	29.9^{b}	32.9^{b}	507^{b}	546^{bc}

Different lowercase letters indicate the significant differences among controlled-release urea placement depths at $P < 0.05$. N0 – non-addition nitrogen fertilisation; D0 – surface broadcasting NPK fertiliser and four NPK fertilisers placed at different depths below the soil surface, recorded as 5 cm (D5), 10 cm (D10), 15 cm (D15) and 20 cm (D20)

NUE values increased by 3.3, 8.0, 9.1 and 8.1% under D5, D10, D15 and D20, respectively (Table 2).

Principal component analysis and correlation analysis. The relationships among the lodging behaviour, stem and root character parameters and grain yield parameters of maize in both years were examined by principal component analysis (PCA) (Figure 6). PCA analysed the stem lodging-related parameters, root lodging-related parameters, and grain yield-related parameters independently, and their first two components explained 79.5, 90.7 and 84.0%, respectively (Figure 6A–C). The stem lodging resistance index positively correlated with the third basal internode's diameter and dry matter weight. Conversely, there was a significant negative correlation between stem lodging rate and the mechanical strength of the third internode and lignin content (Figure 7). Root lodging rate was negatively correlated with aerial root tension, aerial root angle, root length, and root dry weight of 40–60 cm soil layer (Figure 8). Grain yield was negatively correlated with stem lodging and root lodging, while they were positively correlated with yield components.

DISCUSSION

Deep controlled-release urea placement increases grain yield and nitrogen use efficiency. Matching soil nitrogen distribution with crop nitrogen demand is an important method to achieve high grain yield and nitrogen use efficiency. Fertilisation placement depth affects soil nitrogen distribution and, thus, crop yield (Wu et al. 2021). Combined controlled-release urea and deep fertiliser placement have been verified in crop production to improve crop production and nitrogen use efficiency (Qiang et al. 2022, Hu et al. 2023). Our results showed that deep placement of

Table 2. Harvest index, plant dry matter, plant nitrogen accumulation, nitrogen use efficiency (NUE) and nitrogen physical efficiency (NPE) of spring maize under different controlled-release urea placement depths in 2022 and 2023

Depth	Harvest index		Plant dry matter (t/ha)		Plant nitrogen accumulation (kg/ha)		NUE (kg/kg)		NPE (kg/kg)	
	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023
N0	39.6^{d}	42.6^{d}	17.5^{e}	18.1^{e}	13.7^{e}	15.2^{e}	50.8^{c}	50.7^{b}	–	–
D0	46.0^{c}	47.8^{c}	18.1^{d}	19.2^{d}	17.6^{d}	18.6^{d}	47.3^{d}	49.3^{c}	34.7^{d}	38.2^{d}
D5	50.1^{b}	51.0^{b}	19.1^{c}	20.4^{c}	18.6^{c}	19.8^{c}	51.5^{bc}	52.4^{b}	39.9^{c}	43.3^{c}
D10	52.4^{a}	53.4^{a}	20.3^{b}	23.3^{ab}	19.8^{b}	22.7^{ab}	53.8^{ab}	54.8^{ab}	44.4^{ab}	51.8^{ab}
D15	53.4^{a}	53.6^{a}	21.4^{a}	24.0^{a}	20.7^{a}	23.2^{a}	55.2^{a}	55.4^{a}	47.5^{a}	53.6^{a}
D20	50.8^{b}	53.1^{a}	20.3^{b}	22.0^{b}	19.6^{b}	21.3^{b}	52.4^{ab}	54.9^{ab}	42.8^{b}	48.8^{b}

Different lowercase letters indicate the significant differences among controlled-release urea placement depths at $P < 0.05$. N0 – non-addition nitrogen fertilisation; D0 – surface broadcasting NPK fertiliser and four NPK fertilisers placed at different depths below the soil surface, recorded as 5 cm (D5), 10 cm (D10), 15 cm (D15) and 20 cm (D20)

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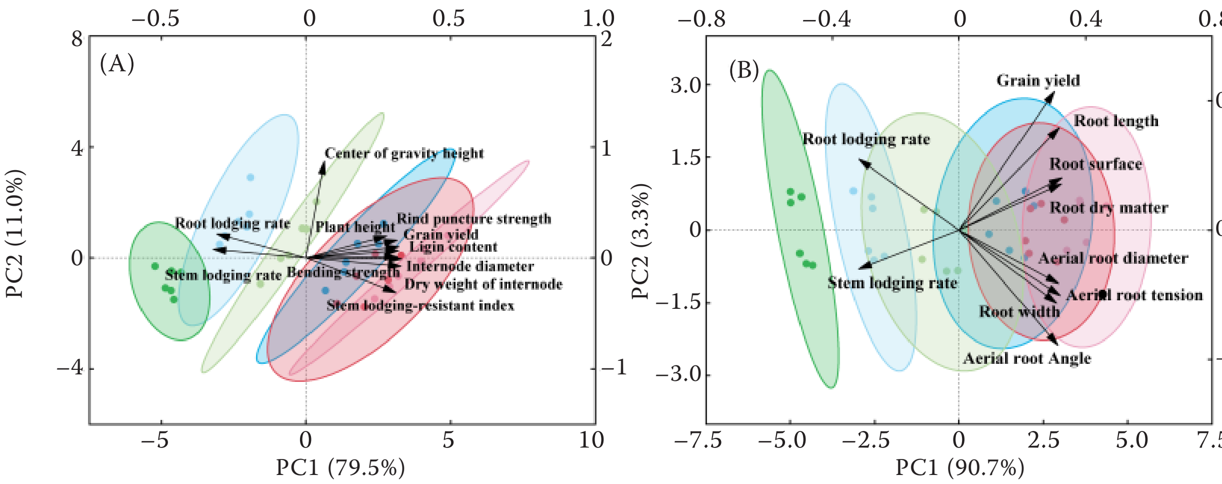

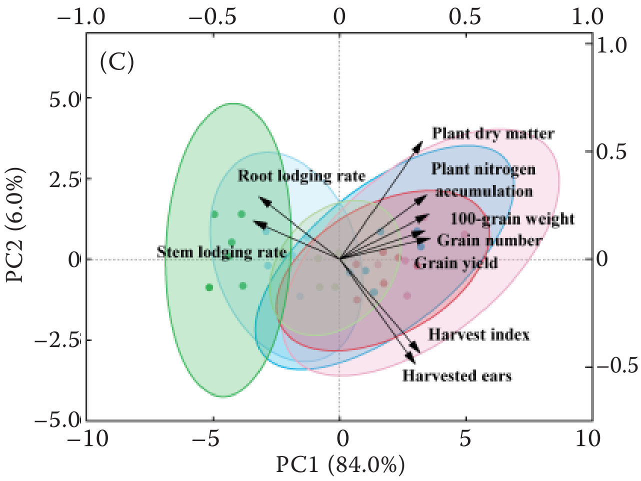

Figure 6. Principal component analysis of (A) the relationships between yield-related parameters and grain yield; (B) the relationships between stem lodging-related parameters and maize stem lodging rate; (C) the relationships between root-related parameters and root lodging rate under different controlled-release urea placement depths in 2022 and 2023

controlled-release urea could increase maize productivity (grain yield, plant dry matter and plant nitrogen accumulation) and nitrogen use efficiency, consistent with previous research results (Chen et al. 2023, Hu et al. 2023). As we all know, nitrogen use efficiency is reduced with the increase of nitrogen application rates (Chen et al. 2015), and deep placement of controlled-release urea could increase maize nitrogen use efficiency even more than that of non-nitrogen fertiliser treatment (N0). This study showed that 100-grain weight, grain number and the number of harvested ears had a remarkable positive correlation with the stem lodging rate (Figure 8). Reasonable fertilisation depths improved the grain yield through the combined effect of maize yield components.

Deep controlled-release urea placement minimises lodging risk (stem and root). Nitrogen fertiliser management strategies to improve maize yield and reduce lodging risk have attracted extensive attention. However, the effects of deep controlled-release urea placement on maize lodging are unclear. In the present study, deep placement of controlled-release urea reduces stem and root lodging. The stem and root lodging rate had a closely negative correlation with grain yield (Figure 8, $P < 0.01$), which implies that maize lodging was mainly stem and root lodging in this region.

Stem morphological structure, mechanical strength and chemical composition determine the lodging resistance of stems in field crops (Berry et al. 2021, Zhang et al. 2023). The current study found deep controlled-release urea placement could improve stem lodging resistance. This is because of the improvement of mechanical stem strength (BS and RPS) as a result of the greater dry weight of the third basal internode and internode diameter in both years and, additionally, as a result of higher lignin content; similar findings were reported by Wu et al. (2019) and Berry et al. (2021). Li et al. (2023) confirmed that deep fertilisation can improve rice lodging resistance by optimising lignin content, which is consistent with our study. In our study, the lignin

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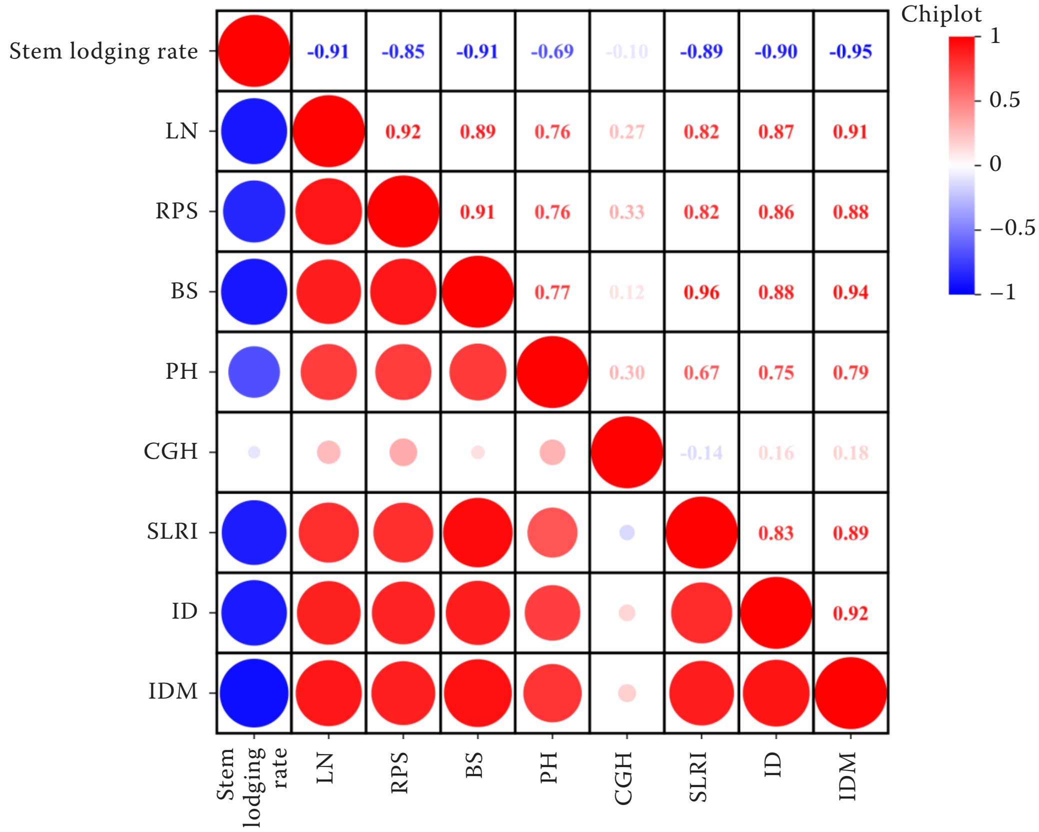

Figure 7. Pearson correlation coefficients between stem lodging-related parameters and maize stem lodging rate. LN – lignin content; RPS – rind puncture strength; BS – bending strength; PH – plant height; CGH – center of gravity height; SLRI – stem lodging-resistant index; ID – internode diameter; IDM – dry weight of internode

content of the third basal internode was significantly greater in D15 than in D0 during successive years (2022–2023). The above result was attributed to the fact that higher plant nutrient status significantly increased the activity of enzymes in lignin biosynthesis in stem (Kamran et al. 2018, Ahmad et al. 2023), while deep controlled-release urea placement could maintain higher nitrogen absorption (Table 2, Chen et al. 2023). This study showed that the diameter, dry matter weight, mechanical strength of the third basal internode and lignin content had a remarkable negative correlation with the stem lodging rate (Figure 7), which is in line with the views of Sekhon et al. (2020) and Li and Li (2021). This means that the stem lodging resistance could be further improved by increasing the third basal internode's BS and RPS, diameter, and dry matter weight. These parameters can be considered as important factors for future variety improvement.

Studies on maize root lodging mainly focus on the relationship among root growth and development, structural characteristics and lodging and usually take root dry weight, root diameter and spread of the root plate as indicators of plant resistance to root lodging (Bian et al. 2016, Kamara et al. 2003, Berry et al. 2021, Sparks 2023). In addition, Liu et al. (2012) showed that aerial roots (as the supporting root system of maize) have a large number, a large diameter, a small angle with the main stem, and a strong resistance to root lodging. Maize roots have strong plasticity, and the appropriate controlled-release urea placement depth can improve the morphological structure and physiological adaptation to improve the roots' anchorage ability. Increasing the depths of controlled-release urea significantly (P < 0.05) reduced the rates of root lodging in both years (Figure 2), thus indicating a smaller risk of root lodging. The results of our study showed that the root surface area, root length, root dry weight, root width, airborne rooting angle, airborne rooting diameter and airborne root tension were relatively higher under the D15 treatment, which showed a lower root lodging rate in both years experiments. This is largely related to NO_3^--N and NH_4^+-N dis-

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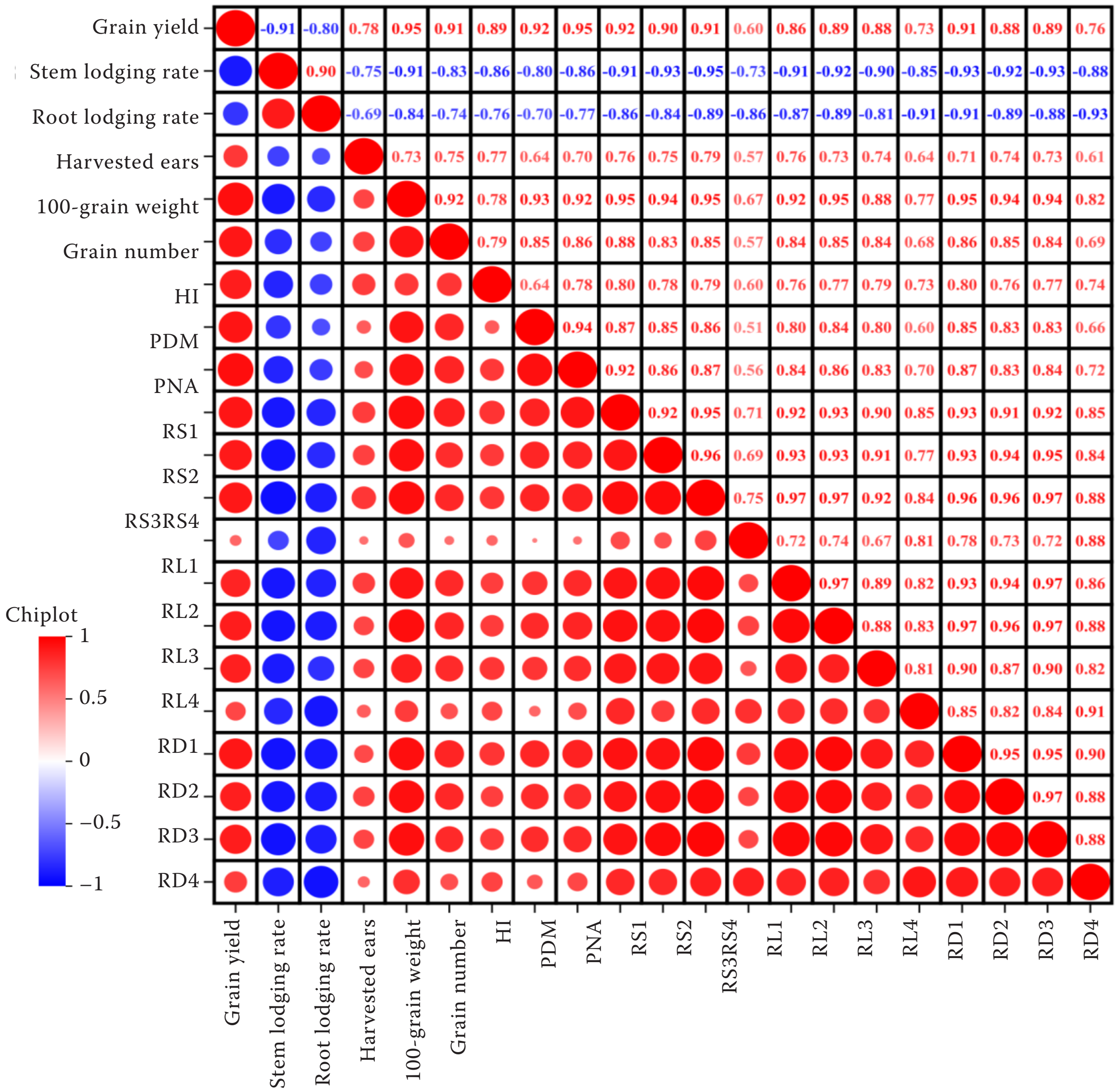

Figure 8. Pearson correlation coefficients between yield-related parameters and grain yield. HI – harvest index; PDM – plant dry matter; PNA – plant nitrogen accumulation; RS1, RL1, RD1 – root surface area, root length, root dry matter in 0–10 cm soil layer; RS2, RL2, RD2 – root surface area, root length, root dry matter in 10–20 cm soil layer; RS3, RL3, RD3 – root surface area, root length, root dry matter in 20–40 cm soil layer; RS4, RL4, RD4 – root surface area, root length, root dry matter in 40–60 cm soil layer

tribution in the root zone (Chen et al. 2023). Also, optimising fertilisation depth can maximise the capacity of maize roots to absorb nutrients by enhancing soil chemical and biochemical characteristics in the root zone (Wu et al. 2024). In addition, studies have shown that suitable fertilisation depth could indirectly reduce soil bulk density, increase soil porosity and enhance soil agglomeration by promoting soil organic carbon and microbial community (Nyamangara et al. 2001, Su et al. 2015, Fan et al. 2020). Soil structure was positively correlated to root number density (Tinashe et al. 2023). It can be seen from the above that deep fertilisation may affect root growth and distribution by affecting soil structure.

In addition, deep controlled-release urea placement promoted deeper root distribution, which is inconsistent with previous findings (Wu et al. 2022, Chen et al. 2023). This study showed that the tensile

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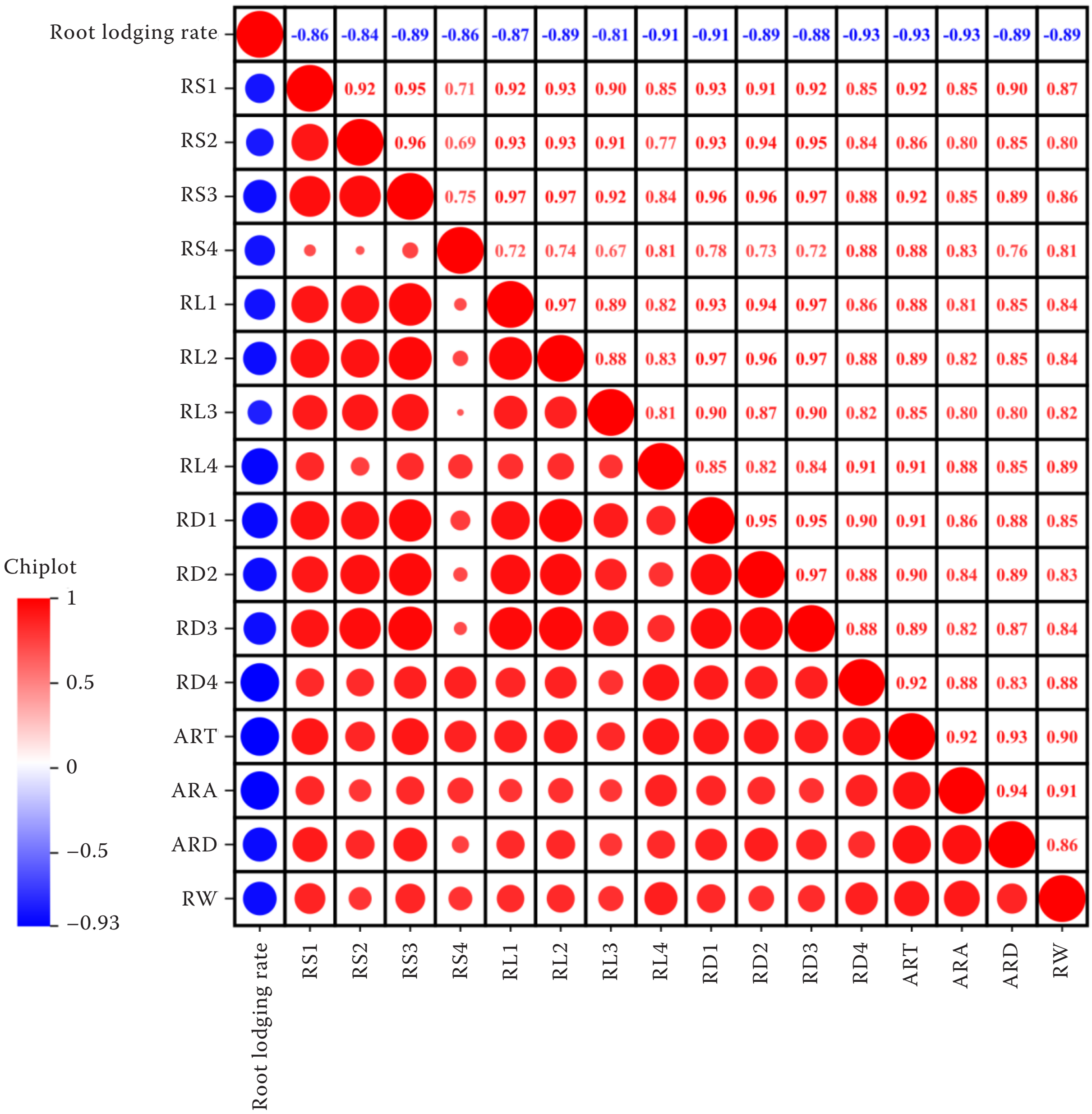

Figure 9. Pearson correlation coefficients between root-related parameters and root lodging rate. RS1, RL1, RD1 – root surface area, root length, root dry matter in 0–10 cm soil layer; RS2, RL2, RD2 – root surface area, root length, root dry matter in 10–20 cm soil layer; RS3, RL3, RD3 – root surface area, root length, root dry matter in 20–40 cm soil layer; RS4, RL4, RD4 – root surface area, root length, root dry matter in 40–60 cm soil layer; ART – aerial root tension; ARA – aerial root angle; ARD – aerial root diameter; RW – root width

force of the aerial root, the diameter of the aerial root, root width, root dry matter and morphology had a remarkable negative correlation with the root lodging rate (Figure 9). This implies that larger and deeper distribution was critical to improving root lodging. It is worth noting that there are also inter-annual differences in root growth. The precipitation of maize growing season in 2023 is higher than in 2022. In 2022, the root surface area, root length and root dry mass of each treatment between 0–40 cm are all smaller than those in 2023, while those indexes between 40–60 cm are all higher than those in 2023. In addition, the higher rate of root lodging in 2023 than in 2022 implies that the root distribution is responsible for this result, which is in agreement with previous findings (Jia et al. 2018).

Under irrigation conditions, root lodging is more likely to occur than stem lodging (Jia et al. 2018). Our results

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showed that the lodging rate accounts for more than 50 per cent of the total lodging rates. The rate of root lodging is higher than stem lodging, especially in years with high rainfall (averages of 2022 and 2023 were 8.7% and 11.07%); this is consistent with Jia et al. (2018). This indicates that root lodging is common in wetter areas and a priority to ensure high yields. Some studies conducted spatial regression analysis on factors affecting maize lodging stress, and found that rainfall is the primary factor inducing lodging, and heavy rainfall is likely to cause soil softness and decrease root fixation ability (Xue et al. 2016). In addition, the stem lodging rate in 2022 is higher than that in 2023 (the average of 2022 and 2023 were 5.27% and 4.3%) due to the weaker stem strength (Figure 3). Previous research (Li et al. 2015) reported that the adverse effect of stem lodging on grain yield was higher than that of root lodging. The relative yield loss rates caused by stem lodging were higher than those of root lodging during the filling period (yield loss rates of 45–48% and 30–38%, respectively). Stem lodging had a greater effect on dry matter transport and thus resulted in a much greater reduction than root lodging, which may explain why in 2023, there was higher root lodging but lower stem lodging than in 2022, and the final yield was higher than in 2022. Although root lodging is positively related to root morphological characteristics, root lodging rate is more closely related to aerial root. For different precipitation years, the precipitation increase has a greater effect on grain yield improvement than root lodging. While stem lodging and root lodging were significantly reduced under the condition of deep controlled-release urea placement, contributing to the reduction of lodging risk.

Correlation analysis showed deep roots were significantly negatively correlated with root lodging rate. Deeper root distribution helps reduce the risk of root lodging, which is agreed upon by Qian et al. (2024). In our study, the relationship between root lodging and root traits was further studied. The results showed that the root lodging rate at the grain filling stage was significantly negatively correlated with root length, root surface area, root dry weight, aerial root tension, aerial root angle, and aerial root diameter. Internode diameter, root surface area, root length and root dry weight were significantly positively correlated with grain yield ($P < 0.01$). These parameters were important for improving stem lodging resistance and maize grain yield. In addition, there was a significant positive correlation between grain yield and root dry weight, root surface and root length, suggesting that promoting root development may be the main way to improve root resistance and grain yield. It is necessary to consider the soil's physical properties from the grain-filling stage to maturity. Studies have shown that returning straw to the field can improve soil quality and thus improve lodging resistance (Qian et al. 2024), which may be another factor leading to the lodging of maize roots, which needs further study.

Controlled-release urea depth recommendation. The results showed that the optimal controlled-released urea placement depth was 15 cm. Suppose the depth of fertilisation reaches 20 cm (in our study) or even excessive root depth (25 cm, Wu et al. 2022, Chen et al. 2023). In that case, the distribution of nitrogen nutrients in the soil is unreasonable, which does not match the root growth, and may lead to insufficient nitrogen supply in the root layer of maize, thus inhibiting the root absorption of nitrogen (Ju et al. 2006). The decrease in crop nitrogen uptake under D20 treatment (Table 2) may be due to the limited nitrogen content in the root layer, which is not conducive to maintaining nitrogen absorption. Wu et al. (2022), the highest maize yield was obtained at a depth of 25 cm (the study was conducted in semi-humid), which was deeper than our study, and the optimal depth of fertiliser placement was related to precipitation. The result on wheat (Wang et al. 2023) showed that nitrogen placement shallower depth during a wet year could effectively maintain crop productivity and nitrogen balance compared with a dry year. The recommended depth agrees with previous studies (Cheng et al. 2020). Therefore, in consideration of maize stem and root lodging resistance and maize productivity, a controlled-release urea placement depth of 15 cm can significantly reduce the risk of lodging and fully dig maize yield potential, thus can be used as a wet region recommended controlled-release urea placement depth of maize productivity. Further experiments are needed to verify the depth of fertilisation in different seasonal precipitation years.

In this work, deep placement of controlled-release urea at 15 cm increased grain weight by increasing dry matter accumulation and harvest index, thereby improving grain yield and nitrogen use efficiency. At the same time, D15 treatment can minimise the risk of stem lodging and reduce the lodging rate by optimising the diameter, dry matter weight, lignin content, and mechanical strength of the third basal internode. In addition, the establishment of larger and deeper root systems, as well as aerial root morphology and tension, can help reduce root lodging. Therefore, deep controlled-release urea placement

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can be used as an effective management strategy to improve maize productivity, nitrogen use efficiency and lodging resistance. More attention has been paid to deep fertiliser application technology, and the deep fertiliser application machinery has been continuously improved (Patuk et al. 2020). The deep loose fertilisation integrated machine has also been produced in our country, which is of great significance for promoting deep fertiliser application technology. Further study must integrate factors such as soil quality, seasonal precipitation, and genotype to determine the depth of fertilisation in agricultural ecosystems.

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