Deep placement of controlled-release urea effectively enhanced nitrogen use efficiency and fresh ear yield of sweet corn in fluvo-aquic soil

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Application of controlled-release urea (CRU) improves crop yield and nitrogen use efficiency (NUE) compared with conventional urea. However, the effectiveness of CRU differs with fertilization placement. A two site-year field experiment was carried out in fluvo-aquic soil in central China to study the effects of two N sources (CRU and urea) and three fertilization placements (band application between two corn rows at 0, 5, and 15 cm soil depths) on fresh ear yield and NUE of sweet corn. The soil inorganic N (NO$_3^-$-n and NH$_4^+$-N) concentrations at the soil layers of 0–20 cm and 20–40 cm, root morphology characteristics and leaf physiological functions were also measured during the sweet corn growth period. Results showed that the deep placement of CRU at 15 cm soil depth significantly increased the sweet corn fresh ear yield, total N uptake, and NUE by 6.3%–13.4%, 27.9%–39.5%, and 82.9%–140.1%, respectively compared with CRU application at 0 cm depth. Deep placement of CRU at 15 cm also increased the root morphology traits, gas exchange attributes, and soil NO$_3^-$-N and NH$_4^+$-N concentrations in 0–20 cm and 20–40 cm layer, especially during later crop growth stages. However, the different N placements exerted non-significant effects on NUE and fresh ear yield when urea was applied as the N source. In crux, deep CRU placement instead of urea at 15 cm depth can effectively improve fresh ear yield and NUE of sweet corn in fluvo-aquic soil because of higher root growth, better leaf physiological functions and increased availability of soil NO$_3^-$-N and NH$_4^+$-N.

Sweet corn (Zea mays L.) cultivation is receiving great attention in China and across the globe because of its high sugar content and unique combination of flavor, texture, and aroma compared with other types of corn. Sweet corn is also an important source of fiber, minerals, and vitamins. The planting areas of sweet corn have rapidly increased in China with the progress of urban agriculture and adjustment of agricultural structure. Nitrogen (N) is an essential element for plant growth and development. Excessive amounts of N fertilizer have been used in China to achieve high yields of field crops, including sweet corn. Nevertheless, excessive N application not only decreases N use efficiency (NUE) but also increases N losses from field soils to the environment through various pathways, thereby deteriorating air, water, and soil qualities. Therefore, improved fertilizer management practices that simultaneously maximize crop yield, minimize environmental impacts, and maintain soil productivity should be explored.

Effective fertilizer placement needs excellent timing according to the demand of the crops and environmental conditions with low risk of nutrient losses. Split fertilizer placement during important growth stages of the crop enhances the uptake of nutrient and final yield. However, applying the appropriate rate and quantity manually is difficult for farmers because it requires time and additional labor costs. The rapid economic development in China has led to an increased demand for high-quality sweet corn, which requires efficient and effective use of N fertilizer.
China has moved rural laborers to developed coastal areas\textsuperscript{15}, resulting in the lack of human labor and its high cost. Therefore, a simple and convenient N fertilizer management is needed for sweet corn production.

The development of a controlled-release N fertilizer technique has potential in addressing the aforementioned issues\textsuperscript{16}. Controlled-release urea (CRU) is introduced to farmers as a new type of N fertilizer for agricultural productions in China, the USA, and even worldwide\textsuperscript{17}. CRU is widely used as an effective mitigation alternative in improving crop productivity and reducing labor inputs\textsuperscript{18}. CRU provides a gradual N supply as per crop requirement for prolonged period\textsuperscript{7,19}. The N release of CRU coordinates with the N requirement pattern of various crops\textsuperscript{7,20–22}, thereby reducing N loss and enhancing soil inorganic N supply, especially at later growth periods\textsuperscript{23,24}. The differences in the environmental conditions can also affect the characteristics of N release and its coordination with crop demand\textsuperscript{25}. For example, a previous study on \textsuperscript{15}N-labeled reported higher maize yield and NUE with CRU than urea\textsuperscript{26}, but some other researchers have reported contrasting results\textsuperscript{27,28}. The different responses of crop yields to CRU suggest the need for further research in order called for additional investigation is required to determine the most effective application method and placement depth in different environmental conditions.

The deep placement of fertilizers, especially urea, efficiently abates N loss, particularly ammonia volatilization, and increases crop yield and NUE\textsuperscript{29–31}. Similar to conventional urea, deep CRU placement effectively increases the productivity of various crops, such as soybean\textsuperscript{32}, summer maize\textsuperscript{33}, and rice\textsuperscript{34}. However, the effects of CRU fertilization with different placements on fresh ear yield and NUE in a sweet corn field remain poorly understood. In the present study, a two-year field experiment was performed to investigate the effect of two N sources, namely, CRU and urea, and three fertilization placement depths on crop N uptake, NUE, and fresh ear yield in sweet corn in fluvo-aquic soil in central China. The specific objectives of this study included (1) evaluating the effects of CRU application with varying placement depths on fresh ear yield and NUE compared with conventional urea application and (2) comparing the dry matter accumulation and N uptake of the aboveground parts, root morphology characteristics, and soil inorganic N (NO\textsubscript{3}\textsuperscript{−} - N and NH\textsubscript{4}\textsuperscript{+} - N) concentrations during the main sweet corn growth stages under different N treatments.

Results

Cumulative release rate of N from CRU in 25 °C water. The N cumulative release rate of CRU followed an “S” shape curve under laboratory conditions (25 °C still water), as shown in Fig. 1. The N release of CRU was slow during the first 24 h, and the N cumulative release rates reached only at 0.7%. This slow release stage indicated that the membrane structure of CRU was relatively complete and that the controlled-release fertilizer had good performance. An accelerated release stage (1–22 days) followed, finishing with a reduced N release stage after 22 days. The N cumulative release rates for CRU reached 80.3% in 63 days.

Fresh ear yield and NUE. Relative to N0, urea application significantly (\(P < 0.05\)) increased fresh ear yield by 13.1% (11.3%–15.8%) in 2016 and 12.9% (11.8%–14.1%) in 2017. The CRU application also significantly (\(P < 0.01\)) increased fresh ear yield by 13.6% (7.8%–22.2%) in 2016 and 11.9% (8.2%–15.0%) in 2017 (Table 1). The highest fresh ear yield was achieved at D15 placement for both N sources. When CRU was applied, the fresh ear yield showed an increasing trend with the increase in fertilization depth from 0 cm (D0) to 15 cm (D15). The fresh ear yield was significantly (\(P < 0.05\)) increased by 13.4% and 6.3% in the CRU application at D15 placement during 2016 and 2017, respectively compared with D0 placement. However, the differences were non-significant (\(P > 0.05\)) in both years among the D0, D5, and D15 placements when urea was applied as the N source.

N source and placement exerted significant effects on NUE in both years (\(P < 0.01\)). The interaction between the N sources and placement was also significant (\(P < 0.01\)) in 2017 (Table 1). With both N sources, NUE presented an increasing trend as fertilization depth was increased from D0 to D15. Across both years, CRU application at D5 and D15 placements increased the NUE significantly (\(P < 0.01\)) compared with urea application at the same placement depths. However, both urea and CRU were statistically similar (\(P > 0.05\)) to each other at D0 (Table 1).

![Figure 1. Nitrogen-accumulated release rate dynamics of CRU in water at 25 °C.](https://doi.org/10.1038/s41598-019-56912-y)
Dry matter and N accumulation. Both N source and placement had non-significant effect ($P > 0.05$) on the aboveground dry matter accumulation at the V6 stage in 2016 and 2017 (Table 2). However, the individual effect of the N source for the aboveground dry matter accumulation from V6 to R3 stages in 2016 ($P < 0.05$) and from VT to R3 stages in 2017 was significant ($P < 0.01$). The effect of N placement was significant ($P < 0.01$) for aboveground dry matter accumulation from VT to R3 stages in 2016 and from V6 to R3 stages in 2017. The interactive effect of N source and placement was also significant ($P < 0.05$) for dry matter accumulation from VT to R3 stages in both years. Compared with N0 treatment, urea application significantly ($P < 0.01$) increased the dry matter accumulation from V6 to R3 stages by 9.0%–21.5% in 2016 and 23.6%–27.8% in 2017. CRU application also significantly ($P < 0.01$) increased dry matter accumulation from V6 to R3 stages by 22.0%–64.1% in 2016.

### Table 1. Effects of nitrogen (N) source and placement on fresh ear yield and N use efficiency (NUE) of sweet corn in 2016 and 2017. Data are presented as the means of three replications. Within a column for each season, values followed by different letters indicate significant difference according to Duncan’s test at $P = 0.05$. **$P < 0.01$; *$P < 0.05$; Ns, $P > 0.05$.**

| Year | Placement | N source | Fresh ear yield (t ha$^{-1}$) | NUE (%) |
|------|-----------|----------|------------------------------|---------|
|      |           |          | 2016 | 2017 | Mean | 2016 | 2017 | Mean |
|      |           | N0       | 12.19 c | 15.30 c | 13.74 d | 11.8 c | 19.4 c | 15.6 c |
| 2016 | D0        | Urea     | 13.69 b | 17.11 ab | 15.40 bc | 8.2 bc | 21.6 c | 19.9 c |
|      |           | CRU      | 13.14 b | 16.56 b | 14.85 c | 18.2 bc | 21.6 c | 19.9 c |
|      | D5        | Urea     | 13.57 b | 17.25 ab | 15.41 bc | 13.9 bc | 21.3 c | 17.6 c |
|      |           | CRU      | 13.48 b | 17.19 ab | 15.34 bc | 23.4 b | 32.1 b | 27.8 b |
|      | D15       | Urea     | 14.12 ab | 17.45 a | 15.79 ab | 20.0 bc | 21.5 c | 20.8 c |
|      |           | CRU      | 14.90 a | 17.60 a | 16.25 a | 43.7 a | 39.5 a | 41.6 a |

### Table 2. Differences in aboveground dry matter weight and accumulation rate during main sweet corn growth stages under different N fertilization treatments in 2016 and 2017. Data are presented as the means of the three replicates. Within a column for each season, values followed by different letters indicate significant difference according to Duncan’s test at $P = 0.05$. V6: sixth leaf stage; VT: tasseling stage; R3: harvest (milk maturity) stage. **$P < 0.01$; *$P < 0.05$; Ns, $P > 0.05$.**
P only increased the Gs. The differences among different N fertilizer treatments were non-significant (SPAD in 2016, and for Gs, Tr, and SPAD in 2017. The highest N accumulation at the VT stage in 2016 was observed in CRU application at D15 placement. Urea application at D15 placement recorded the highest N accumulation at the VT stage in 2017, but the difference was non-significant (\( P < 0.05 \)) and from VT to R3 stages in 2017 (\( P < 0.05 \)). The highest N accumulation at the VT stage in 2016 was observed in CRU application at D15 placement. CRU application at D15 placement resulted in the highest dry matter accumulation rate from V6 to R3 stages in 2016 and from VT to R3 stages in 2017.

### Table 3. Effect of N source and placement on aboveground N accumulation on sweet corn growth stages in 2016 and 2017. Data are presented as the means of three replicates. Within a column for each season, values followed by different letters indicate significant difference according to Duncan’s test at \( P = 0.05 \). V6: sixth leaf stage; VT: tasseling stage; R3: harvest (milk maturity) stage. **: \( P < 0.01 \); *: \( P < 0.05 \);

| Year | Placement | N source | V6 (kg ha\(^{-1}\)) | VT (kg ha\(^{-1}\)) | R3 (kg ha\(^{-1}\)) | Before V6 (kg ha\(^{-1}\)) | V6 to VT (kg ha\(^{-1}\)) | VT to R3 (kg ha\(^{-1}\)) |
|------|-----------|----------|---------------------|---------------------|---------------------|-----------------------------|---------------------------|---------------------------|
| 2016 | D0        | Urea     | 8.0 a               | 38.0 b              | 104.4 c             | 0.32 a                     | 1.20 ab                   | 2.66 cd                   |
|      | CRU       | 7.3 a    | 34.5 b              | 115.9 bc            | 0.29 a              | 1.09 bc                    | 3.25 bcd                  |
|      | D5        | Urea     | 7.3 a               | 29.5 c              | 108.1 bc            | 0.29 a                     | 0.89 cd                   | 3.14 bcd                  |
|      | CRU       | 8.0 a    | 35.6 b              | 125.2 b             | 0.32 a              | 1.11 bc                    | 3.58 b                    |
|      | D15       | Urea     | 7.6 a               | 33.8 bc             | 119.0 bc            | 0.30 a                     | 1.05 bc                   | 3.41 bc                   |
|      | CRU       | 7.8 a    | 43.3 a              | 161.7 a             | 0.31 a              | 1.42 a                     | 4.74 a                    |

ANOVA

| N source | Placement | Ns | Ns | Ns | Ns | Ns | Ns | Ns |
|----------|-----------|----|----|----|----|----|----|----|
| N source | Ns | **  | Ns | Ns | ** | Ns | Ns | Ns |
| Placement | Ns | Ns | ** | Ns | Ns | ** | Ns | Ns |
| N source x placement | Ns | Ns | Ns | Ns | Ns | Ns | Ns | Ns |

ANOVA

| N source | Placement | Ns | Ns | Ns | Ns | Ns | Ns | Ns |
|----------|-----------|----|----|----|----|----|----|----|
| N source | Ns | Ns | ** | Ns | Ns | ** | Ns | Ns |
| Placement | *  | ** | ** | *  | ** | ** | Ns | Ns |
| N source x placement | *  | Ns | ** | Ns | Ns | ** | Ns | Ns |

and 17.9%–36.3% in 2017. Compared with urea application, CRU application increased dry matter accumulation significantly (\( P < 0.05 \)) from V6 to R3 stages by 9.1%, 16.1%, and 35.1% at D0, D5, and D15 placements in 2016, respectively. Compared with D0 placement, urea application at D15 placement increased dry matter accumulation after V6 stage by 8.6% and 3.4% in 2016 and 2017 (\( P > 0.05 \)), respectively. However, the corresponding increase in dry matter accumulation after V6 stage was 34.5% and 15.6% by CRU application in 2016 and 2017, respectively (\( P < 0.05 \)). CRU application at D15 placement resulted in the highest dry matter accumulation rate from V6 to R3 stages in 2016 and from VT to R3 stages in 2017.

Similarly, N source had a significant effect on the aboveground N accumulation from V6 to R3 stages in 2016 (\( P < 0.05 \)) and from VT to R3 stages in 2017 (\( P < 0.01 \)). Placement had a significant effect on the aboveground N accumulation from VT to R3 stages in 2016 (\( P < 0.01 \)) and from V6 to R3 stages in 2017 (\( P < 0.05 \)) (Table 3). The highest N accumulation at the VT stage in 2016 was observed in CRU application at D15 placement. Urea application at D15 placement recorded the highest N accumulation at the VT stage in 2017, but the difference was non-significant (\( P > 0.05 \)) between the CRU application at D5 and D15 placements. Consistent to dry matter accumulation rate, CRU application at D15 placement also resulted in the highest N accumulation rate from V6 to R3 stages in 2016 and from VT to R3 stages in 2017.

### Root morphological characteristics.

Data on root morphology characteristics, including root length, surface area, and volume at the VT stage, are provided in Table 4. The N placement had a significant effect on root surface area and volume at the VT stage in 2016 (\( P < 0.05 \)) and on root length, surface area, and volume at the VT stage in 2017 (\( P < 0.05 \)). The individual effect of N source and the interaction between N source and placement had non-significant effect (\( P > 0.05 \)) on the root morphology attributes in both years. The highest values for these root morphological parameters at the VT stage were observed in CRU application at D15 placement in both years.

### Leaf physiological functions.

The leaf area index (LAI), net photosynthetic rate (Pn), stomatal conductance (Gs), transpiration rate (Tr), and SPAD value of sweet corn at the VT stage are presented in Table 5. N source had a significant effect on the LAI, and N placement had a significant effect on the Pn in 2017 (\( P < 0.01 \)). However, both N source and placement did not affect LAI and Pn significantly (\( P > 0.05 \)) in 2016. The highest LAI and Pn at the VT stage were observed in CRU application at D15 placement in both years. N source also had a significant effect on the Tr in 2016, and placement had a significant effect on the Gs in 2016. In 2016, CRU application at D15 placement significantly (\( P < 0.05 \)) increased the Gs and Tr, whereas deep placement of urea only increased the Gs. The differences among different N fertilizer treatments were non-significant (\( P > 0.05 \)) for SPAD in 2016, and for Gs, Tr, and SPAD in 2017.
### Table 4. Root morphological characteristics of sweet corn at VT stage in 2016 and 2017. Data are presented as the means of three replicates. Within a column for each season, values followed by different letters indicate significant difference according to Duncan's test at \( P = 0.05 \). VT, tasseling stage. **\( P < 0.01 \); *\( P < 0.05 \); Ns, \( P > 0.05 \).

| Year | Placement | N source | Root length (cmplant\(^{-1}\)) | Root surface area l (cm\(^2\)) | Root volume (cm\(^3\) plant\(^{-1}\)) |
|------|-----------|----------|--------------------------------|---------------------------------|---------------------------------|
| 2016 | N0        | Urea     | 1715.7 b                        | 915.1 b                         | 23.8 c                          |
|      | D0        | Urea     | 1880.3 b                        | 904.5 b                         | 26.8 bc                         |
|      | D5        | Urea     | 2258.6 ab                       | 963.0 b                         | 27.4 bc                         |
|      | D15       | Urea     | 2725.2 a                        | 1070.4 ab                       | 37.1 ab                         |
|      | CRU       |          | 2372.3 ab                       | 945.7 b                         | 30.5 bc                         |
|      | CRU       |          | 2803.2 a                        | 1286.1 a                        | 47.3 a                          |

ANOVA

N source Ns Ns Ns  
Placement Ns * **  
N source \( \times \) placement Ns Ns Ns

| Year | Placement | N source | LAI | Pn   | Gs   | Tr   | SPAD |
|------|-----------|----------|-----|------|------|------|------|
| 2016 | D0        | Urea     | 1.48 b | 26.7 c | 0.29 c | 6.9 b | 33.7 b |
|      | CRU       |          | 1.90 a | 49.0 ab | 0.38 c | 10.2 ab | 44.9 a |
|      | D5        | Urea     | 1.80 ab | 46.0 b | 0.38 c | 7.1 b | 46.9 a |
|      | CRU       |          | 1.74 ab | 52.8 ab | 0.58 b | 10.3 ab | 43.4 a |
|      | D15       | Urea     | 1.73 ab | 55.1 ab | 0.79 a | 9.2 ab | 46.8 a |
|      | CRU       |          | 1.91 a | 59.5 a | 0.74 a | 12.3 a | 48.2 a |

ANOVA

N source Ns Ns Ns ** Ns  
Placement Ns Ns ** Ns Ns  
N source \( \times \) placement Ns Ns Ns Ns Ns

### Table 5. Effects of N source and placement on leaf area index (LAI), photosynthesis rate (Pn, \( \mu \text{mol CO}_2 \text{ m}^{-2} \text{s}^{-1} \)), stomatal conductance (Gs, mmol H\(_2\)O m\(^{-2}\) s\(^{-1}\)), transpiration rate (Tr, mmol H\(_2\)O m\(^{-2}\) s\(^{-1}\)), and chlorophyll content (SPAD, %) of sweet corn at the VT stage in 2016 and 2017. Data are presented as the means of three replicates. Within a column for each season, values followed by different letters indicate significant difference according to Duncan's test at \( P = 0.05 \). **\( P < 0.01 \); *\( P < 0.05 \); Ns, \( P > 0.05 \).

| Year | Placement | N source | LAI | Pn   | Gs   | Tr   | SPAD |
|------|-----------|----------|-----|------|------|------|------|
| 2016 | D0        | Urea     | 1.76 ab | 42.5 a | 0.40 c | 7.8 b | 45.2 a |
|      | CRU       |          | 1.90 a | 49.0 ab | 0.38 c | 10.2 ab | 44.9 a |
|      | D5        | Urea     | 1.80 ab | 46.0 b | 0.38 c | 7.1 b | 46.9 a |
|      | CRU       |          | 1.74 ab | 52.8 ab | 0.58 b | 10.3 ab | 43.4 a |
|      | D15       | Urea     | 1.73 ab | 55.1 ab | 0.79 a | 9.2 ab | 46.8 a |
|      | CRU       |          | 1.91 a | 59.5 a | 0.74 a | 12.3 a | 48.2 a |

ANOVA

N source Ns Ns Ns ** Ns  
Placement Ns Ns ** Ns Ns  
N source \( \times \) placement Ns Ns Ns Ns Ns

| Year | Placement | N source | LAI | Pn   | Gs   | Tr   | SPAD |
|------|-----------|----------|-----|------|------|------|------|
| 2017 | N0        | Urea     | 2.06 d | 37.9 b | 0.32 a | 3.7 a | 52.4 a |
|      | D0        | Urea     | 2.47 bc | 39.8 b | 0.38 a | 3.8 a | 55.3 a |
|      | D5        | Urea     | 2.34 c | 49.4 a | 0.32 a | 4.1 a | 54.8 a |
|      | CRU       |          | 2.56 ab | 38.3 b | 0.39 a | 4.2 a | 55.5 a |
|      | D15       | Urea     | 2.56 ab | 42.3 b | 0.34 a | 4.1 a | 57.2 a |
|      | CRU       |          | 2.70 a | 50.4 a | 0.31 a | 4.1 a | 57.3 a |

ANOVA

N source Ns ** Ns Ns Ns  
Placement ** Ns Ns Ns Ns  
N source \( \times \) placement Ns Ns Ns Ns Ns
Soil inorganic N concentration. The NO$_3^-$-N and NH$_4^+$-N concentrations at the soil depths of 0–20 cm and 20–40 cm during the two years are listed in Table 6. In 2016, the effect of N source and placement on soil NH$_4^+$-N concentrations at 0–20 cm and 20–40 cm soil depths was non-significant ($P > 0.05$) at all the three growth stages. N source significantly affected the NO$_3^-$-N concentration of the soil depths of 0–20 cm at the VT stage ($P < 0.01$) and 20–40 cm at the R3 stage in 2016 ($P < 0.05$). Fertilizer placement only significantly affected the NO$_3^-$-N concentration of 0–20 cm soil depth at the VT stage in 2016 ($P < 0.01$). In 2017, N source showed significant effects on the NO$_3^-$-N concentrations of the soil depths of 0–20 cm and 20–40 cm at the three stages ($P < 0.05$) and the NH$_4^+$-N concentration of the soil depth of 0–20 cm at the VT stage and 20–40 cm at both V6 and VT stages ($P < 0.05$). The N placement also significantly affected the NO$_3^-$-N concentrations of the soil depth of 20–40 cm at the V6 and VT stages in 2017 ($P < 0.05$). The NH$_4^+$-N and NO$_3^-$-N concentrations of the soil depth of 0–20 cm in CRU application at D5 and D15 placements were significantly higher than those in urea application treatments from V6 to R3 stages in 2017 ($P < 0.05$). The NO$_3^-$-N concentrations at soil depth of 20–40 cm in CRU application at D5 and D15 placements were also significantly higher than those in urea application treatments at the VT and R3 stages in 2017 ($P < 0.05$).

Discussion

Considerable studies have been carried out to compare the effects of varying fertilizer application methods on nutrient use efficiency and crop productivity. Generally, deep fertilization placement in soil can increase fertilizer use efficiency and crop yield compared with surface or shallow application. For instance, Yao et al. indicated that deep N placement in paddy fields increased the rice yield and NUE by 10% and 55%, respectively, compared with surface broadcasting. Guo et al. showed that deep CRU placement increases the N uptake and NUE of maize on clay loam soil. In the present study, deep CRU placement significantly improved the NUE and fresh ear yield of sweet corn by 109.04% and 9.43%, respectively compared with CRU application at 0 cm depth, averaged across two years (Table 1). These results are similar to those of previous studies on maize, soybean, and rice. However, the effect of different N placement on crop yield of sweet corn when conventional urea was used as N source (Table 1) and these findings contradict with the results reported by Smith et al. Yao et al. also reported that deep urea placement in intensive rice cropping system can provide NH$_4^+$-N concentration in the soil during the early growth stage and extend N availability duration for two months. The different results for urea in the present study might be due to variations in environmental conditions such as rainfall pattern and soil properties, cultivars, and agronomic practices (e.g. fertilization, irrigation, and tillage). Moreover, greater NUE and fresh ear yield with deep placement of CRU might be attributed to enhancement in root morphology attributes in the present study. Compared with D0, CRU application at D15 significantly increased the root surface area and root volume by 48.19% and 73.90%, respectively averaged across two years. Nevertheless, these two root attributes remained statistically for urea application at D0 and D15. These better performance of deep placement of CRU over urea has previously been reported in rice, possibly due to slow release of CRU.

The results of the present study revealed significant variations in soil NO$_3^-$-N and NH$_4^+$-N concentrations (Table 6), thereby indicating that environment factors, such as temperature and precipitation, regulated soil inorganic N dynamics in sweet corn field. The soil NH$_4^+$-N concentrations at the three stages in 2016 ranged from 2.2 mg kg$^{-1}$ to 3.8 mg kg$^{-1}$ at the soil depth of 0–20 cm and from 1.1 mg kg$^{-1}$ to 4.0 mg kg$^{-1}$ at the soil depth of 20–40 cm. These values were significantly lower than those in 2017 (5.3–232.2 mg kg$^{-1}$ at 0–20 cm soil depth and 4.4–44.9 mg kg$^{-1}$ at 20–40 cm soil depth; Table 6). However, the soil NO$_3^-$-N concentrations at the three stages in 2016, especially at the soil depth of 0–20 cm, were higher than those in 2017. Such results can be ascribed to the differences in climatic conditions, especially precipitation and temperature. In the present study, an increase in the soil inorganic N concentration (especially NO$_3^-$-N content in 20–40 cm soil layers) was observed at the later growth stage of sweet corn under CRU deep placement (D15) compared with that under D0 or D5 (Table 6). This increase was possibly due to the increase in the contact of N fertilizer granules with soil and decrease in N losses through runoff and NH$_3$ volatilization. Therefore, the enrichment of plant available N concentration also promoted the aboveground dry matter accumulation and N uptake in sweet corn plants (Tables 2 and 3) and ultimately improved the NUE and fresh ear yield (Table 1 and S1). Better root growth (Table 4 and S2) and leaf physiological functions (LAI, Pn, Gs, Tr, and SPAD) (Table 5 and S2) at the VT stage may also explain the higher NUE, total N uptake, and fresh ear yield under deep placement of CRU.

In our study, deep placement of CRU and urea significantly affected the soil inorganic N concentration during the different growth stages of sweet corn, which can be associated with the nitrification–denitrification processes in soil. However, the magnitude of nitrification–denitrification under deep CRU and urea placement is unclear. Therefore, the responses of N processes to deep CRU and urea placement need to be explored. In general, the available N in the plant root zone (0–40 cm soil layer) soil samples and NO$_3^-$-N concentration of CRU treatment were higher than those in urea treatments, especially for D15 placement (Table 6). A possible reason for such results might be the losses of urea-N through leaching into underground water. Compared with urea, the release of N in CRU is slow, and only a small amount of N is leached into underground water. This also indicates that CRU can increase the amount of available N in the plant root zone and decrease the risk of N losses.

Conclusions

The results of this study revealed that deep placement of urea did not significantly affect the fresh ear yield and NUE of sweet corn. However, deep placement of CRU at 15 cm depth significantly enhanced the fresh sweet corn ear yield and NUE. The higher fresh ear yield and NUE of sweet corn under deep CRU placement were attributed to improved root growth, better leaf physiological functions and increased soil NO$_3^-$-N and NH$_4^+$-N concentrations, especially during the later growth stages of sweet corn.
### Table 6. Effect of N source and placement on soil NH$_4^+$-N (mg kg$^{-1}$) and NO$_3^-$-N (mg kg$^{-1}$) concentrations in the 0–20 cm and 20–40 cm depths during main sweet corn growth periods in 2016 and 2017. Data are presented as the means of three replicates. Within a column for each season, values followed by different letters indicate significant difference according to Duncan's test at $P = 0.05$. V6: sixth leaf stage; VT: tasseling stage; R3: harvest (milk maturity) stage.

| Year | Placement | N source  | V6  | VT  | R3  |
|------|-----------|-----------|-----|-----|-----|
|      |           | 0–20 cm   | 20–40 cm | 0–20 cm | 20–40 cm | 0–20 cm | 20–40 cm |
|      |           |          |       |     |     |       |       |
| 2016 | N0        | 2.9 a     | 3.2 a  | 3.4 a | 3.8 a  | 3.4 a  | 2.5 a  |
|      | D0        | 2.2 a     | 3.0 a  | 3.1 a  | 3.2 a  | 4.3 a  | 3.1 a  |
|      | CRU       | 2.3 a     | 3.2 a  | 3.4 a  | 3.4 a  | 3.5 a  | 3.2 a  |
|      | D5        | 3.0 a     | 3.4 a  | 3.2 a  | 3.4 a  | 3.2 a  | 1.1 a  |
|      | CRU       | 2.5 a     | 3.3 a  | 3.0 a  | 3.4 a  | 3.4 a  | 1.3 a  |
|      | D15       | 2.4 a     | 4.0 a  | 3.2 a  | 3.2 a  | 1.5 a  | 1.5 a  |
|      | CRU       | 3.8 a     | 3.5 a  | 3.6 a  | 2.3 a  | 1.5 a  | 1.5 a  |
|      | ANOVA     | N source  | Ns    | Ns    | Ns    | Ns    | Ns    |
|      |           | Placement | Ns    | Ns    | Ns    | Ns    | Ns    |
|      |           | N source $\times$ placement | Ns    | Ns    | Ns    | Ns    | Ns    |

| Year | Placement | N source  | V6  | VT  | R3  |
|------|-----------|-----------|-----|-----|-----|
|      |           | 0–20 cm   | 20–40 cm | 0–20 cm | 20–40 cm | 0–20 cm | 20–40 cm |
|      |           |          |       |     |     |       |       |
| 2017 | N0        | 6.4 a     | 7.4 ab | 6.7 c  | 2.9 b  |
|      | D0        | 5.7 b     | 84.3 bc | 9.5 bc  | 5.7 b   |
|      | CRU       | 10.5 ab   | 115.3 abc | 7.8 c    | 5.7 b    |
|      | D5        | 13.1 a    | 125.0 ab | 17.4 a   | 13.1 a   |
|      | CRU       | 14.2 a    | 78.6 c  | 14.2 a   | 14.2 a   |
|      | D15       | 9.6 ab    | 102.2 abc | 12.3 ab  | 9.6 ab   |
|      | CRU       | 16.7 a    | 137.5 a  | 16.7 a   | 16.7 a   |
|      | ANOVA     | N source  | Ns    | Ns    | Ns    | Ns    | Ns    |
|      |           | Placement | Ns    | Ns    | Ns    | Ns    | Ns    |
|      |           | N source $\times$ placement | Ns    | Ns    | Ns    | Ns    | Ns    |

**P < 0.01; *P < 0.05; Ns, P > 0.05.**
Materials and Methods

Experimental site. The experiments were carried out in two different fields (1.8 km apart) located in Ezhou City (30°21′ N, 114°45′ E), Hubei Province, central China during the sweet corn growing seasons (August–October) in 2016 and 2017. The soil type in the two fields was typical fluvo-aquic soil (entisol according to USDA classification). The soil physico-chemical properties of the soil layers of 0–20 cm and 20–40 cm prior to experiments are presented in Table 7. The atmospheric temperature and rainfall during two years of sweet corn growing seasons are provided in Fig. 2. Compared with the average annual climatic conditions in the region, the total rainfall during the sweet corn growth season in 2016 (272 mm) was less than that in 2017 (530 mm). Minimal rainfall was observed from mid-August to late September in 2016.

Experimental design and management. Experiment was comprised of seven treatments, including two N sources (CRU and conventional urea), three fertilization placement depths (0 cm as D0, 5 cm as D5, and 15 cm as D15), and a control (N0) without N fertilization treatment. The treatments were arranged in a randomized block design with three replications. The planting pattern of sweet corn was wide-narrow row planting, which was consistent with the conventional growing conditions in China. Urea and CRU were applied in narrow rills of the desired depth (0, 5, and 15 cm) ditched manually between two maize rows sown at 40 cm distance. The soil was leveled after fertilizer placement. CRU is a polymer-coated fertilizer that is manufactured and supplied by the South China Agricultural University and contains 44% N with the nutrient release period of 60 days, while conventional urea containing 46% N was provided by the Hubei Sanning Chemical Co., Ltd. (Hubei, China). The application rates of nutrients in each treatment except N0 included 180 kg N ha⁻¹, 45 kg P₂O₅ ha⁻¹, and 90 kg K₂O ha⁻¹, which were similar to the local farming recommendations. The fertilizers were all applied at the basal dose 1 day before sowing. Each plot area for sweet corn plantation was 20 m² (length × width of 8.3 m × 2.4 m).

Two sweet corn varieties, namely, Fotian 2 (in 2016) and Jintian 678 (in 2017), which were selected by a farmer according to the market, were used in the study. The planting density was 50,000 plants ha⁻¹ (narrow row spacing of 40 cm, wide row spacing of 80 cm, and plant spacing of 33 cm) in both years. The sweet corn seeds were sown on August 1, 2016 and August 3, 2017, and the fresh ears were harvested on October 18, 2016 and October 19, 2017. In addition to the treatments under the study, all the other field management practices, including variety selection and weed, disease, and insect control, throughout the growing season were similar and followed the recommended practices by the local agriculture department.

Sampling and analysis. At the sixth leaf (V6; 25 days after sowing [DAS]) in 2016, 26 DAS in 2017), tasseling (VT; 50 DAS in 2016, 55 DAS in 2017), and harvest (milk maturity) stages (R3; 75 DAS in 2016, 79 DAS in 2017), eight soil subsamples near the plant row (four on each side) were collected in each plot at 0–20 cm and 20–40 cm depths using a stainless steel auger and then mixed to obtain a single composite sample of the same layer. The soil samples were extracted with 2 M KCl (1:10 soil to extractant ratio, 30 min of shaking), and NO₃⁻-N and NH₄⁺-N concentrations were measured using an automated flow injection analyzer (AA3, Bran and Luebbe, Norderstedt, Germany).

| Year | Depth (cm) | Organic matter (g kg⁻¹) | Total N (g kg⁻¹) | NH₄⁺-N (mg kg⁻¹) | NO₃⁻-N (mg kg⁻¹) | Available P (mg kg⁻¹) | Available K (mg kg⁻¹) | pH |
|------|------------|-------------------------|-----------------|------------------|------------------|---------------------|----------------------|----|
| 2016 | 0–20       | 15.1                    | 1.3             | 2.7              | 15.1             | 14.7                | 197.9                | 7.8 |
|      | 20–40      | 10.3                    | 0.7             | 2.3              | 7.6              | 2.6                 | 103.4                | 7.9 |
| 2017 | 0–20       | 28.5                    | 2.6             | 9.3              | 10.3             | 26.4                | 182.5                | 7.3 |
|      | 20–40      | 20.1                    | 1.4             | 7.8              | 4.1              | 16.9                | 114.0                | 7.2 |

Table 7. Physical and chemical properties of soils (0–20 cm and 20–40 cm depths) prior to sowing in 2016 and 2017.
At the same three stages, the aboveground tissue samples were collected from five representative plants in each replicate of the treatment. The leaves, stems and leaf sheaths, tassels, bracts, rachis, and grains were separated and oven dried for 30 min at 105 °C and at 70 °C to a constant weight in determining the dry matter weight. The N concentration of each part was analyzed using H2SO4–H2O2 digestion and a continuous flow injection analyzer (AA3, Bran and Luebbe, Norderstedt, Germany). N uptake was calculated by multiplying the dry matter weight with their respective concentrations in different aboveground parts.

Similarly, at the V6 and VT stage, the three representative roots sampled from each plot were carefully washed and used to measure the root morphology, including root L, surface area, and volume, via WinRhizo software (WinRhizo, Regent Ltd., Canada).

Leaf length and width were measured at the VT stage as described above from the five representative plants, and the leaf area (LA) was then calculated as follows: LA = length × width × K, where K is 0.75 for fully expanded leaves and 0.5 for incompletely expanded leaves. The leaf area index (LAI) was calculated as the sum of the green LA of the five plants divided by the area occupied by those plants. Five sweet corn ear leaves at the VT stage were selected in each plot in measuring the Pn, Gs, and Tr by using a Li-6400XT portable photosynthesis system (Li-Cor, USA) in the morning from 9:00–11:00. The chlorophyll content (SPAD) of the ear leaves was verified with a SPAD-502 chlorophyll meter (Minolta, Osaka, Japan). At the R3 stage, 40 consecutive ears were harvested in each plot to determine the fresh ear yield.

Nitrogen release rates of CRU were tested in a laboratory by incubating in 25 °C water. In brief, 10.0 g of CRU sample were placed in a glass bottle containing 200 ml of distilled water with three replicates, and then kept in a constant temperature incubator at 25 °C. The solution samples were collected at 1, 3, 5, 7, 10, 13, 16, 19, 22, 28, 35, 42, 49, 56, and 63 days or when the cumulative N release rate was more than 80%. The released N content from the CRU was determined using the Kjeldahl method, followed by calculating rates of N release from the CRU.

**Calculations.** The NUE was calculated according to López-Bellido et al.:

\[ \text{NUE}(\%) = \frac{(T_N - T_0)}{F_N} \times 100\% \]

where \( T_N \) and \( T_0 \) are the total N uptake at milk harvest stage from the N-fertilized and unfertilized N0 plots (kg N ha\(^{-1}\)), respectively, and \( F_N \) is the N fertilization rate (kg N ha\(^{-1}\)).

**Data analysis.** The experimental data were statistically analyzed using SPSS 16.0 software. Two-way ANOVA was used to evaluate the effects of N source, placement, and interactions among factors. The differences among treatments were calculated using the Duncan method at \( P = 0.05 \). The figures were prepared via SigmaPlot 10.0 software.

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Additional information

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Author contributions

W. L. and Y. X. initiated and designed the research. W. L., X. X., H. X. and J. Y. performed the experiments. W. L., S. H. and Y. X. analyzed the data and wrote the manuscript. F. X. and S. H. revised and edited the manuscript.

Competing interests

The authors declare no competing interests.

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