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Nitrogen application increases water use efficiency and economic benefit of spring mung bean-summer sweet maize cropping system on the North China Plain

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KEYWORDS

Cropping system, economic equivalent yield, N application, spring mung bean-summer sweet maize, water use efficiency

HIGHLIGHTS

- Nitrogen application increased annual maize equivalent yield and economic benefit of spring mung bean-summer sweet maize copping system.
- Nitrogen application exerted seasonally complementary effects on evapotranspiration.
- Nitrogen application improved water use efficiency in mung bean season and annual.
- Lower nitrogen application rates are recommended for balancing productivity, economy and water sustainability.

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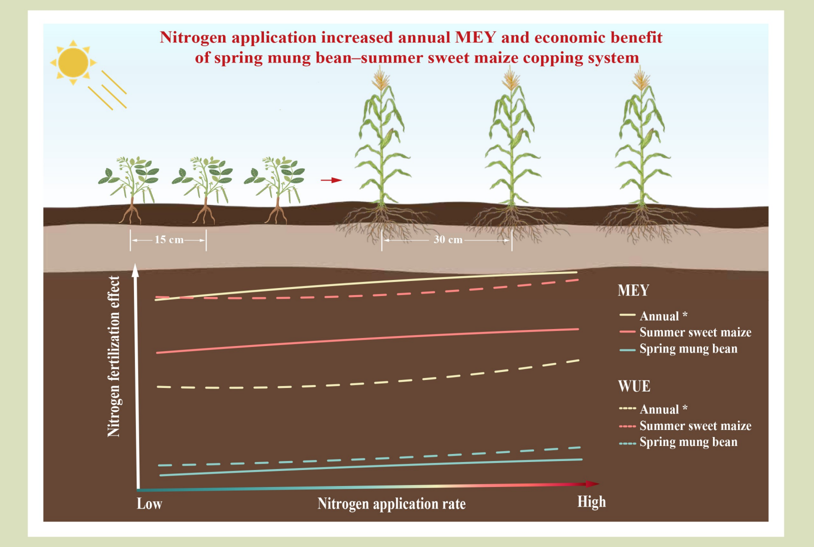
GRAPHICAL ABSTRACT



ABSTRACT

The spring mung bean-summer sweet maize cropping system can alleviate groundwater scarcity problems on the North China Plain. However, the effects of nitrogen application on water use efficiency (WUE) and economic benefit of spring mung bean-summer sweet maize cropping system remain unclear. This study investigated the crop yield, economic benefit and WUE of spring mung bean-summer sweet maize cropping system under four N application regimes:

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N0, no N for spring mung bean and summer sweet maize; N1, 60 and 60 $kg \cdot ka^{-1}$ N for spring mung bean and summer sweet maize, respectively; N2, 60 and 120 $kg \cdot ka^{-1}$ N for spring mung bean and summer sweet maize, respectively; and N3, 60 and 180 $kg \cdot ka^{-1}$ N for spring mung bean and summer sweet maize, respectively. The results indicated that N application significantly increased annual maize equivalent yield (MEY), and N1 and N3 increased annual MEY by 8.6% and 10.7% ($p < 0.05$), respectively, compared to N0 in 2021. N application significantly influenced evapotranspiration (ET) in spring mung bean and summer sweet maize seasons ($p < 0.05$). N1 and N2 decreased ET by 15.1% and 18.9%, respectively, in spring mung bean season, and increased ET by 14.4% and 18.8%, respectively, in summer sweet maize season compared to N0 in 2021, respectively ($p < 0.05$). N3 improved annual WUE by 10.2% and 11.4% compared to N0 in 2020 and 2021, respectively ($p < 0.05$). Also, experimental year significantly affected MEY, ET and WUE in spring mung bean and summer sweet maize seasons, and annually ($p < 0.001$), which can be attributed to the variations in seasonal rainfall between the two experimental years. In summary, N application increased grain yield and WUE of spring mung bean-summer sweet maize cropping system, however, a lower N application rate was recommended to achieve a balance between economic benefit and WUE on the North China Plain.

1 Introduction

Severe water scarcity on the North China Plain (NCP) is driven by the irreconcilable conflict between limited water availability and intensive agricultural production. This region only possesses 7% of China's total water resources, but contributes to over 20% of national grain output[1]. Winter wheat-summer maize cropping system is the dominant cropping system which critically depends on groundwater extraction to ensure its normal growth and yield formation[2], with annual agricultural withdrawals of 2.1×10^{10} $m^3 \cdot yr^{-1}$. The irrigation water for wheat accounting for more than 40% of total irrigation, which further exacerbates the shortage of groundwater resources on the NCP[3,4]. Hence, optimizing cropping system and adopting water-saving practice have significant potentials for reducing water use and achieving sustainable agricultural development on the NCP.

N application is important for increasing grain yield and water use efficiency (WUE) for main crops, such as rice[5], wheat[6] and maize[7]. It has been reported that crop WUE improves with increase in N application at a certain range, but it declines under high N application rates[8,9]. At present, excessive application N fertilizers is used to maintain high yield and improve economic benefit of crop production on the NCP[10]. However, this overuse of N fertilizers not only reduces crop WUE but also results in N surpluses and pollution, which makes the water shortage situation even more severe[11]. Therefore, it is of great importance to optimize suitable amount of N fertilizers input to balance grain yield and WUE at the system level on the NCP.

Legumes have been considered to be a good option in crop rotations to reduce N input and improve soil fertility, because they have the ability to fix atmospheric N, which can remain in the soil to be taken up by the subsequent crops[12–14]. It has been found that summer peanut-winter wheat cropping system with a lower N input can maintain system yield compared to summer maize-winter wheat cropping system on the NCP[15]. Also, crop rotation with legumes increased the system-wide WUE compared with continuous wheat cropping system on the Loess Plateau in China[16]. Therefore, understanding how N application affects crop yield and WUE of water-saving cropping systems can contribute to the balance of crop production and water use for sustainable agricultural development on the NCP.

For this study, we conducted a two-year field experiment to investigate how N application affected yield and WUE of spring mung bean-summer maize cropping system, which has economic and environmental benefits than the common winter wheat-summer maize cropping system on the NCP[13]. Our aims were: (1) to reveal the dynamics in crop yield, economic benefit, and WUE of spring mung bean-summer sweet maize cropping system under different N application regimes; and (2) to optimize the suitable N application rate for spring mung bean-summer sweet maize cropping system in balancing of crop production and water saving.

2 Materials and methods

2.1 Study site description

The experiment was conducted from April 2020 to October 2021 at the Wuqiao Experimental Station of China Agricultural University (37°41′ N, 116°36′ E), Cangzhou City, Hebei Province, China. The regional climate is a typical subhumid continental monsoon climate with an annual temperature of 12.6 °C and cumulative temperature (⩾ 0 °C) of 4826 °C[17]. The frost-free period is 201 days and the mean annual precipitation is 562 mm, which mainly concentrated from June to August. The soil is a medium loamy tidal soil[18]. Initial property of the 0–20 cm soil layer were: soil organic carbon 16.1 g·kg^{-1}, total nitrogen 1.02 g·kg^{-1}, available phosphorus 20.3 mg·kg^{-1}, available potassium 87.5 mg·kg^{-1}, and soil pH 8.0. The accumulated precipitation was 120 and 196 mm in spring mung bean seasons and 196 mm and 444 mm in summer sweet maize seasons in 2020 and 2021, respectively. Daily precipitation and mean air temperature during the experimental periods are shown in Fig. 1.

2.2 Experimental design and agronomic managements

A field experiment was set in a randomized block design with four N application regimes within spring mung bean-summer sweet maize cropping system. The four treatments were: (1) no N for spring mung bean and summer sweet maize, N0; (2) 60 kg·ha^{-1} N for spring mung bean and 60 kg·ha^{-1} N for summer sweet maize, N1; (3) 60 kg·ha^{-1} N for spring mung bean and 120 kg·ha^{-1} N for summer sweet maize, N2; and (4) 60 kg·ha^{-1} N for spring mung bean and 180 kg·ha^{-1} N for summer sweet maize, N3. The amount of P and K fertilizers applied were 47.5 kg·ha^{-1} P and 94.0 kg·ha^{-1} K for spring mung bean, and 75.9 kg·ha^{-1} P and 125.0 kg·ha^{-1} K for summer sweet maize with superphosphate and potassium sulfate, respectively. The treatment plot covered 36 m^2 (4.5 m × 8 m) in three replicates. All fertilizers were applied as base fertilizers before crop sowing.

The crop cultivars were BL13-653 for spring mung bean and

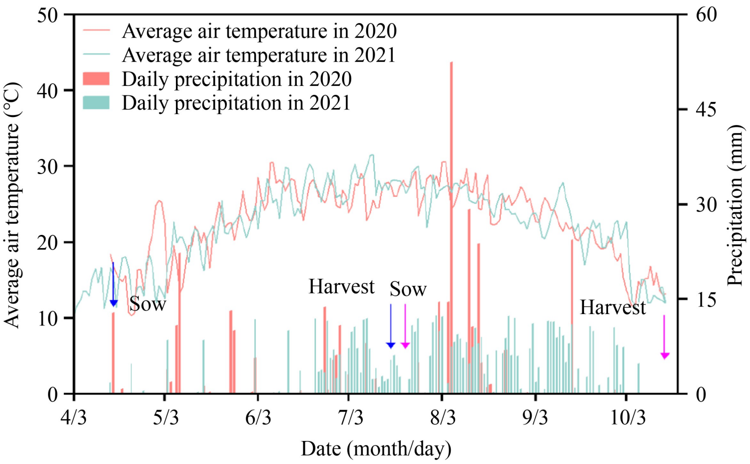

Fig. 1 Daily precipitation and average air temperature during the experimental period at the Wuqiao Experimental Station in 2020 and 2021.

Zhongnongda Tian 413 for summer sweet maize. Spring mung bean was sown on 20 April and harvested on 15 July, and summer sweet maize was sown on 15 July and harvested on 14 October in both experimental years. The row spacing was 40 cm × 15 cm with strip planting for spring mung bean and 60 cm × 30 cm for summer sweet maize. The sowing density was 167,000 plants ha^{-1} for spring mung bean and 56,000 plants ha^{-1} for summer sweet maize. Irrigation of 75 mm was applied before sowing to promote seed germination for both crops, except for summer sweet maize in 2021 due to a high presowing precipitation. Other field managements were performed as local recommended.

2.3 Sampling and measurements

2.3.1 Grain yield and economic benefit

Grain yield was measured from two area of 1.6 m^2 (2 m long × 0.8 m wide, 2 rows) and 3.6 m^2 (3 m long and 1.2 m wide, 2 rows) at the maturity stage for spring mung bean and summer sweet maize, respectively. In order to compare the annual yield, yield of spring mung bean and summer sweet maize was converted into maize equivalent yield (MEY, $kg{\cdot}ha^{-1}$) as[19]:

$$\mathrm{MEY} = \mathrm{Y}_{\text{non-maize}} \times \frac{\mathrm{P}_{\text{non-maize}}}{\mathrm{P}_{\text{maize}}} \tag{1}$$

where, $Y_{\text{non-maize}}$ is the yield of spring mung bean or summer sweet maize ($kg{\cdot}ha^{-1}$), $P_{\text{non-maize}}$ is the price of spring mung bean or summer sweet maize ($USD{\cdot}kg^{-1}$) and P_{maize} is the price of grain maize ($USD{\cdot}kg^{-1}$). The average price was 1.29, 0.46 and 0.32 $USD{\cdot}kg^{-1}$ for spring mung bean, summer sweet maize and grain maize, respectively, in 2020 and 2021 being the market price at harvest. Annual MEY is the sum of MEY of spring mung bean and summer sweet maize.

The total output and net economic income were calculated as[20]:

$$\text{Total output} = \mathrm{Y}_{\text{crop}} \times \mathrm{P}_{\text{crop}} \tag{2}$$

$$\text{Net income} = \text{Total output} - \text{Total input} \tag{3}$$

where, Y_{crop} is the yield of spring mung bean or summer sweet maize ($kg{\cdot}ha^{-1}$) and P_{crop} is the price of spring mung bean or summer sweet maize ($USD{\cdot}kg^{-1}$). Total output is the sum of income of spring mung bean and summer sweet maize. Total input includes the cost of seed, fertilizer application, electricity, fuel, pesticide, and labor. The calculated value of input and output is shown in Table S1.

2.3.2 Evapotranspiration and water use efficiency

Soil moisture (%) was determined by the oven-drying method at 105 °C, and soil samples were collected to a depth of 0–100 cm using a 3-cm diameter auger at intervals of 20 cm in each cell. Soil moisture was calculated as:

$$\text{Soil moisture} = \frac{\mathrm{W_w} - \mathrm{W_d}}{\mathrm{W_w}} \times 100\% \tag{4}$$

where, W_w is the wet weight of soil sample (g) and W_d is the dry weight of soil sample (g).

Soil water storage (SWS, mm) was calculated as[21]:

$$\mathrm{SWS} = \mathrm{SWC} \times \rho_b \times \mathrm{SD} \tag{5}$$

where, SWC (%) is soil water contents, ρ_b ($g{\cdot}cm^{-3}$) is bulk density and SD (mm) is soil depth.

Evapotranspiration (ET, mm) for the crop growth period was calculated as[21]:

$$\mathrm{ET} = \mathrm{P} + \mathrm{I} + \Delta\mathrm{SWS} \tag{6}$$

where, P and I are the total precipitation (mm) and irrigation (mm) during crop growing period, and ΔSWS is the change of soil water storage in the 0–100 cm soil layer during crop growing period (mm).

Due to the flat terrain and deep groundwater table of the region, the contributions of surface runoff, deep drainage and capillary rise to ET are generally negligible[22]. Soil water measurements, together with the absence of waterlogging throughout the crop growth period, indicating that drainage at the site was minimal. Therefore, deep percolation was not considered in the calculation. Upward water flow into the root zone was also negligible because the groundwater table had dropped to about 30 m below the surface[23]. In addition, since the time interval between harvest of the former crop and sowing of the latter crop is short, soil moisture at harvest of the former crop was taken as soil moisture before sowing of the latter crop.

WUE ($kg{\cdot}ha^{-1}{\cdot}mm^{-1}$) of spring mung bean or summer sweet maize or annual was calculated as[24]:

$$\mathrm{WUE} = \frac{\mathrm{MEY}}{\mathrm{ET}} \tag{7}$$

2.4 Data analysis

All data was analyzed by IBM SPSS statistics version 25 (IBM

Corp, Armonk, NY, USA). The normality and homoscedasticity tests were performed on the data set using Shapiro and Levene's tests, respectively. One-way analysis of variance (ANOVA) and Duncan multiple comparison were conducted to analyze maize equivalent yield, economic benefit, ET and WUE of spring mung bean, summer sweet maize or annual for the N application treatments at $p < 0.05$. Two-way ANOVA was conducted for the data when considering the experimental year. All figures were visualized using Origin version 2021 (OriginLab Corp., Northampton, MA, USA).

3 Results

3.1 Maize equivalent yield and economic benefit

Two-way ANOVA showed that experimental year significantly affected MEY in spring mung bean and summer sweet maize seasons, and annually, respectively ($p < 0.001$), and N application significantly affected annual MEY ($p < 0.05$) (Table 1). Compared to N0, N application increased annual MEY by 2.5%–7.5% in 2020 and by 7.3%–10.7% in 2021 (Fig. 2). The MEY of spring mung bean in N1 was 17.9% higher ($p < 0.05$) than in N0 and MEY of summer sweet maize in N3 was 10.7% higher ($p < 0.05$) than in N0 in 2021. However, there was no significant difference in MEY between N1, N2 and N3 (Fig. 2(b)). As for economic benefit, N1 and N3 increased the output by 8.6% and 10.7% ($p < 0.05$) compared to N0 in 2021, respectively (Table S2).

3.2 Soil moisture and crop evapotranspiration

N application showed a rare effect on soil moisture in the 0–100 cm soil depth during the experimental period (Fig. 3). In spring mung bean season, the average soil moisture in 0–100 cm soil depth was 16% in all treatments in 2020 and was 16%, 17%, 17% and 16% in N0 to N3 in 2021, respectively. In summer sweet maize season, the average soil moisture was 14%, 14%, 15% and 15% in N0 to N3 in 2020 and was 21% in all treatments in 2021, respectively. Two-way ANOVA showed that N application and experimental year significantly affected ET in both spring mung bean and summer sweet maize seasons ($p < 0.05$) (Table 1). Compared to N0, the ET in N1 and N2 was 15.1% and 18.9% lower in spring mung bean season, while that was 14.4% and 18.8% higher in summer sweet maize season in 2021, respectively ($p < 0.05$) (Fig. 4(b)). Over the full years, there was no significant differences between the fertilizer application treatments (Fig. 4).

3.3 Water use efficiency

Two-way ANOVA showed that experimental year significantly

Table 1 Effects of experimental year, N application and their interaction on maize equivalent yield (MEY), evapotranspiration (ET) and water use efficiency (WUE) in spring mung bean and summer sweet maize seasons, and annually

Item	Experimental year	N application	Experimental year × N
MEY			
Spring mung bean	***	ns	ns
Summer sweet maize	***	ns	ns
Annual	***	*	ns
ET			
Spring mung bean	*	*	*
Summer sweet maize	***	*	ns
Annual	***	ns	ns
WUE			
Spring mung bean	***	ns	ns
Summer sweet maize	***	ns	ns
Annual	***	*	ns

Note: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; and ns, no significant difference.

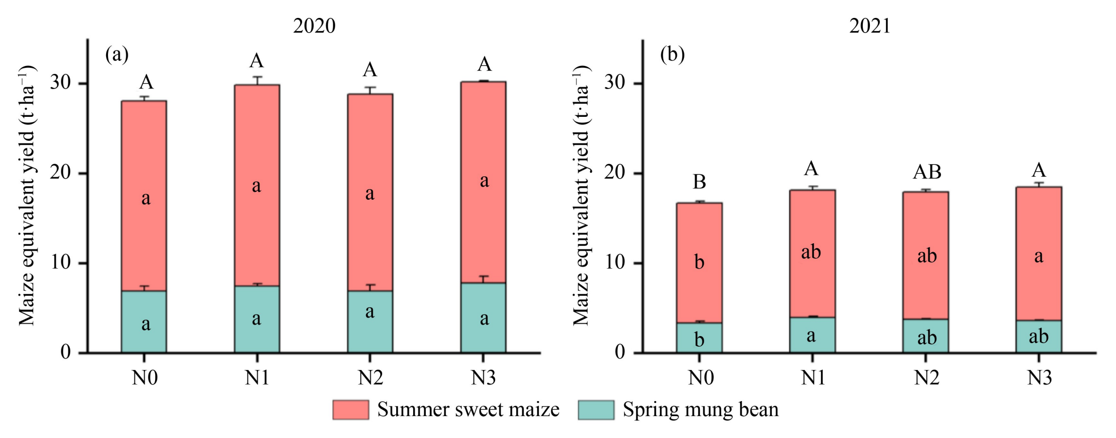

Fig. 2 Maize equivalent yield (MEY) in spring mung bean and summer sweet maize seasons under four N application regimes in 2020 (a) and 2021 (b). Values are means + standard errors ($n = 3$). Means with the same lowercase letters are not significant different ($p < 0.05$) between N application treatments in spring mung bean or summer sweet maize season, respectively. Means with the same uppercase letters are not significant different ($p < 0.05$) between N application treatments annually. N0, no N for spring mung bean and summer sweet maize; N1, 60 kg·ha^{-1} N for spring mung bean and 60 kg·ha^{-1} N for summer sweet maize; N2, 60 kg·ha^{-1} N for spring mung bean and 120 kg·ha^{-1} N for summer sweet maize; and N3, 60 kg·ha^{-1} N for spring mung bean and 180 kg·ha^{-1} N for summer sweet maize.

affected WUE in spring mung bean and summer sweet maize seasons, and annually ($p < 0.001$), while N application significantly affected annual WUE ($p < 0.05$) (Table 1). Compared to N0, the WUE of N1 and N2 in 2021 were 39.2% and 37.4% higher ($p < 0.05$) in spring mung bean season (Fig. 5(b)), and 7.5% and 10.6% lower ($p < 0.05$) in summer sweet maize season, respectively (Fig. 5(d)). Over both years, N application increased the WUE by 0.2%–18.1%, especially in N3 with 10.5% and 9.5% in 2020 and 2021 ($p < 0.05$), respectively.

4 Discussion

4.1 Effect of N application on maize equivalent yield and economic benefit

Our results show that N application affected the annual MEY of spring mung bean-summer sweet maize cropping system to some extent (Table 1). Previous studies have confirmed that N application increased crop yields, including summer sweet maize[25] and spring mung bean[26]. N application can affect crop yield by directly providing N or indirectly changing the nutrient status in the soils[27]. Generally, different N application rates had significant effects on crop yield[28]. However, there was no significant difference in annual MEY between N1, N2 and N3 in 2020. The MEY of N1 in spring mung bean season and N3 in summer sweet maize season is the highest, but there was no difference in annual MEY between these three N application treatments in 2021 (Fig. 2). This can be attributed to the combined influence of the lower fertilizer application requirement of legumes compared to cereal crops, the yield-enhancing effects of legumes on subsequent crops under low N application conditions[29], and variations in rainfall patterns, indicating that the interannual effect masked the responses to N application effects. Economic benefits of the four treatments in two experimental years were consistent with the performance of MEY (Table S2). This could be because not applying N gives only a minor reduction in input costs and therefore did not improve their economic benefits. In our study, the experimental year had a significant effect on MEY (Table 1), mainly due to the differences in precipitation between the two experimental years (Fig. 1), and maize yield normally correlated positively with precipitation fluctuation[30]. Additionally, the previous long-term winter wheat-summer maize cropping system in the field made the excessive soil N surplus can explain the differences in two experimental years rather than between fertilizer application treatments[31,32].

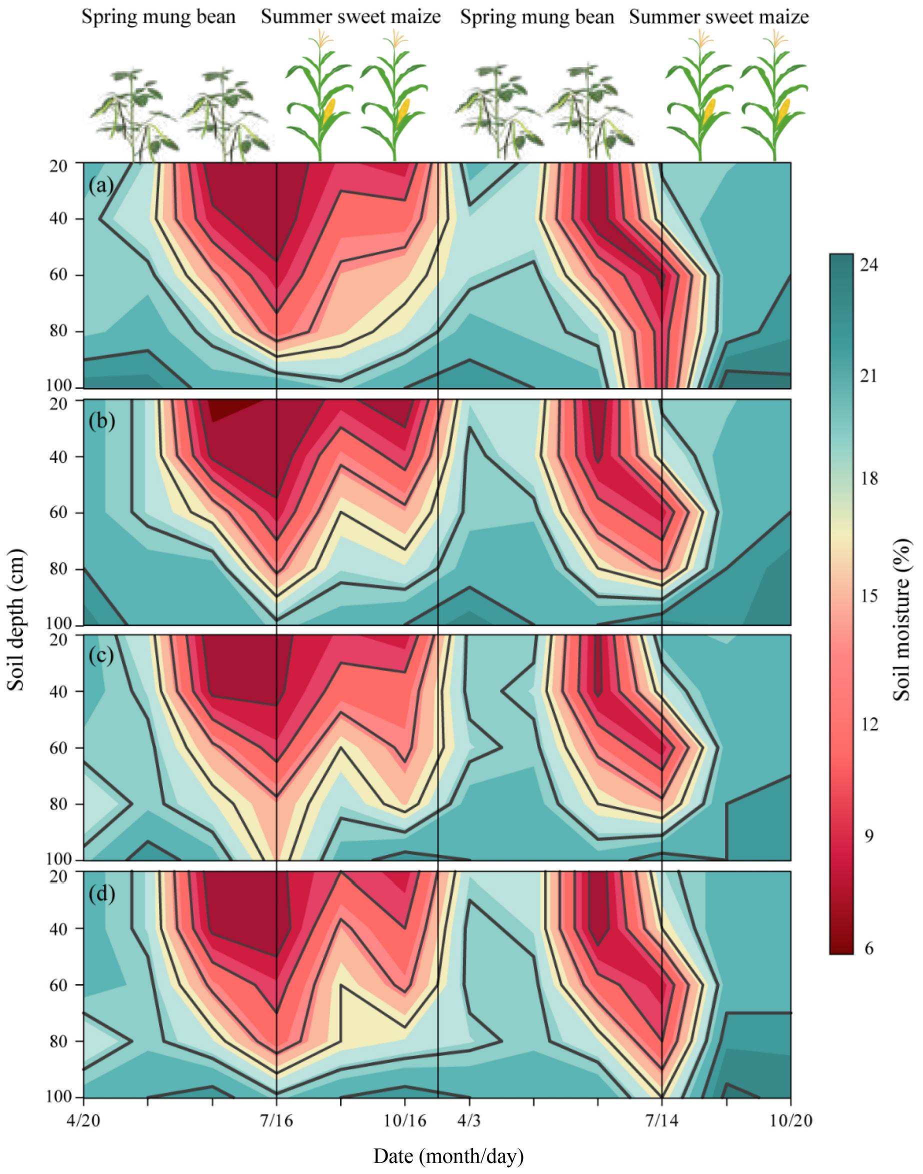

Fig. 3 Changes of soil moisture in the 0–100 cm soil depth in spring mung bean and summer sweet maize seasons of spring mung bean-summer sweet maize cropping system under four N application regimes: N0 (a); N1 (b); N2 (c); and N3 (d)) in 2020 and 2021. Values are means (*n* = 3). N0, no N for spring mung bean and summer sweet maize; N1, 60 kg·ha^{-1} N for spring mung bean and 60 kg·ha^{-1} N for summer sweet maize; N2, 60 kg·ha^{-1} N for spring mung bean and 120 kg·ha^{-1} N for summer sweet maize; and N3, 60 kg·ha^{-1} N for spring mung bean and 180 kg·ha^{-1} N for summer sweet maize.

4.2 Effect of N application on soil moisture and evapotranspiration

N application increases soil moisture during the fallow period[33]. N application affected soil moisture mainly by influencing transpiration or soil evaporation during plant growth in a temperate steppe[34]. In our study, soil moisture in four treatments did not change significantly, but it significantly affected ET in spring mung bean and summer sweet maize seasons (Table 1). This was mainly reflected in crop ET in both seasons in the second experimental year, as no N application

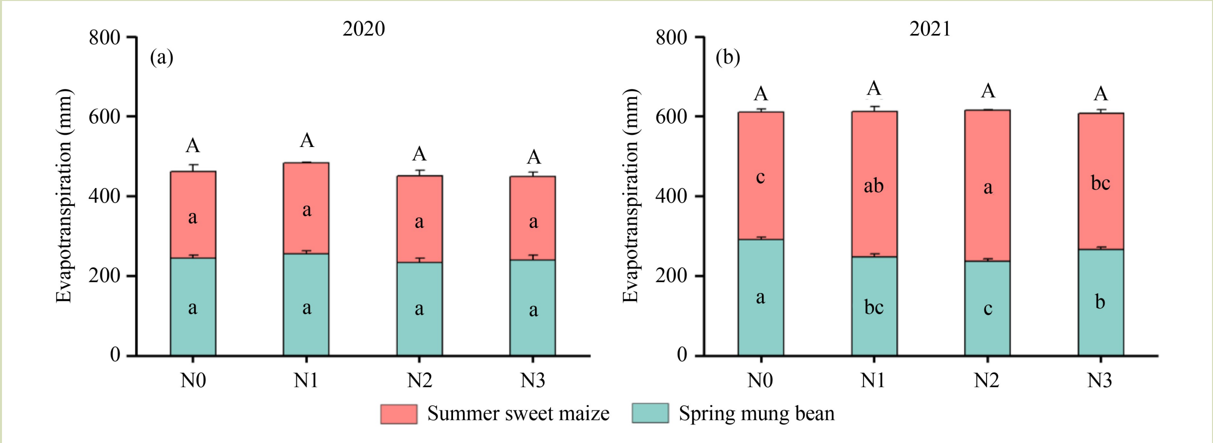

Fig. 4 Total evapotranspiration in spring mung bean and summer sweet maize seasons under four N application regimes in 2020 (a) and 2021 (b). Values are means + standard errors (n = 3). Means with the same lowercase letters are not significant different ($p < 0.05$) between N application treatments in spring mung bean or summer sweet maize season, respectively. Means with the same uppercase letters are not significant different ($p < 0.05$) between N application treatments for annually. N0, no N for spring mung bean and summer sweet maize; N1, 60 kg·ha^{-1} N for spring mung bean and 60 kg·ha^{-1} N for summer sweet maize; N2, 60 kg·ha^{-1} N for spring mung bean and 120 kg·ha^{-1} N for summer sweet maize; and N3, 60 kg·ha^{-1} N for spring mung bean and 180 kg·ha^{-1} N for summer sweet maize.

(N0) had a higher ET in spring mung bean season, while N application (N1 to N3) increased ET in summer sweet maize season (Fig. 4). Some studies found that N application increased ET as it increased yield and meanwhile raised crop water demand[35,36]. This was consistent with the water consumption pattern in summer sweet maize season under different N application treatments. In contrast, not applying N to legumes significantly increased the number and quality of root nodules[37]. It may lead to an increase in water consumption of legumes under no N application conditions[38]. Also, it was notable that there was a complementary relationship between water consumption in spring mung bean and summer sweet maize seasons under the four N application treatments in 2021, leading to no difference in the annual total water consumption in these treatments (Fig. 3). This may be due to the complementary water use between the two crops[39].

4.3 Effect of N application on water use efficiency

Effect of N application on crops is also reflected in WUE[40]. Previous studies have demonstrated that increased N application can improve crop WUE[41,42] and optimizing N application was also shown to be an effective way to optimize water and N use in a study of N application on water productivity[43]. In our study, we conducted a novel spring mung bean-summer sweet maize double cropping system as a water-saving alternative to replace the widely-used winter wheat-summer maize cropping system, and found both N application and experimental year had significant effects on system level WUE (Table 1). Despite significant differences between the two experimental years, all N applications increased WUE to varying degrees. Of these, N1 and N3 had significant differences in WUE compared with N0 in 2021 (Fig. 5(f)). This result was mainly due to the fact that N application increased the annual WUE by increasing the total annual MEY (Fig. 2). The different N application strategies were also found to have varying effects on WUE in spring mung bean and summer sweet maize seasons in the second experimental year. All N application treatments increased WUE in spring mung bean season, but in summer sweet maize season, N1 and N2 decreased WUE, and N3 increased WUE (Fig. 5). This may be due to differential crop responses to N application rate, as the optimal N application level varies between maize and mung bean[44,45]. These findings further demonstrate that the spring mung bean-summer sweet maize cropping system not only allows flexible adjustment of N application rates to balance productivity and WUE but also offers substantial potential for improving resource use efficiency and water-saving performance at the cropping system level.

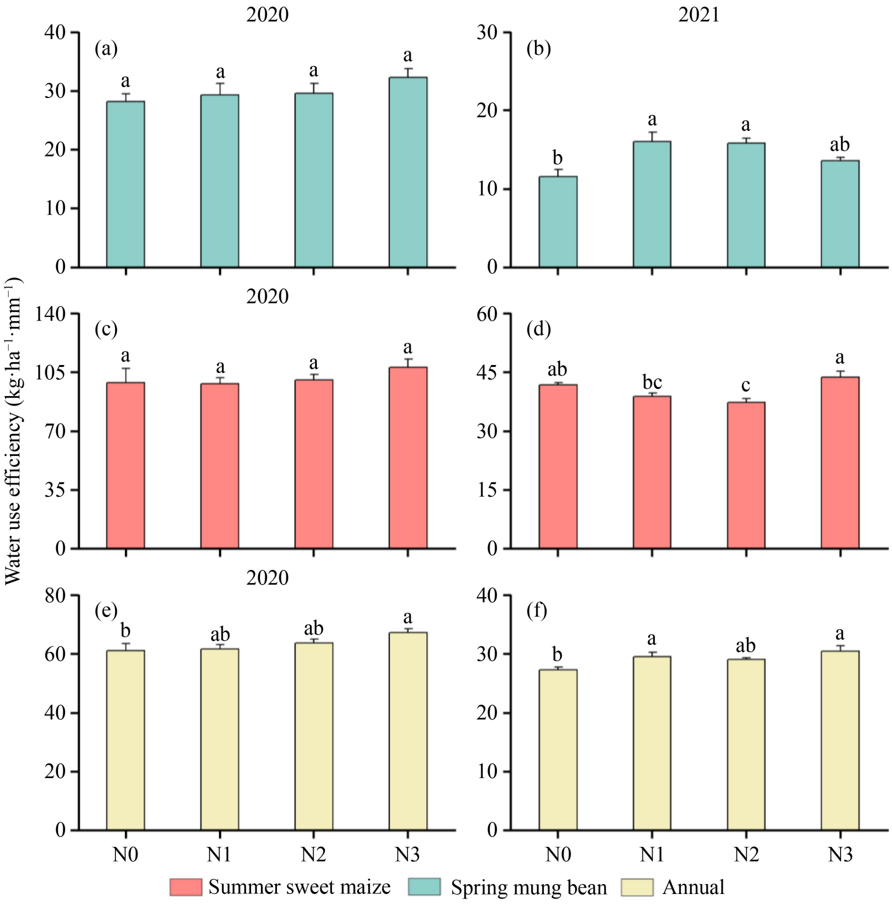

Fig. 5 Water use efficiency of spring mung bean-summer sweet maize cropping system under four N application regimes in spring mung bean (a, b) and summer sweet maize (c, d) seasons, and annually (e, f) in 2020 and 2021. Values are means + standard errors (*n* = 3). Means with the same lowercase letters are not significant different ($p < 0.05$) between N application treatments in spring mung bean or summer sweet maize season or annual, respectively. N0, no N for spring mung bean and summer sweet maize; N1, 60 kg·ha^{-1} N for spring mung bean and 60 kg·ha^{-1} N for summer sweet maize; N2, 60 kg·ha^{-1} N for spring mung bean and 120 kg·ha^{-1} N for summer sweet maize; and N3, 60 kg·ha^{-1} N for spring mung bean and 180 kg·ha^{-1} N for summer sweet maize.

5 Conclusions

Our two-year field experiment demonstrated that N application increased grain yield, economic benefit, and water use efficiency of spring mung bean-summer sweet maize cropping system. N application increased annual MEY, WUE and total output by 7.3%–10.7%, 4.8%–9.5% and 7.3%–10.7%, respectively. Between N fertilized treatments, the low N application rate helped balance crop production and WUE. In conclusion, the lower N application rates are recommended for spring mung bean-summer sweet maize cropping system for crop production and water use under the goal of sustainable agricultural development on the North China Plain.

Supplementary materials

The online version of this article at http://doi.org/10.15302/J-FASE-2026680 contains supplementary materials (Tables S1–S2).

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Compliance with ethics guidelines

Yicong Zhang, Xiqing Hou, Yueqiang Tong, Yangkang Huang, Bangwei Zhang, Zhaohai Zeng, and Yadong Yang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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