N-fertilizer postponing application improves dry matter translocation and increases system productivity of wheat/maize intercropping

Ke Xu1,2, Qiang Chai1,2*, Falong Hu1,2, Zhilong Fan1,2 & Wen Yin1,2

Intercropping increases the grain yield to feed the ever-growing population in the world by cultivating two crop species on the same area of land. It has been proven that N-fertilizer postponed topdressing can boost the productivity of cereal/legume intercropping. However, whether the application of this technology to cereal/cereal intercropping can still increase grain yield is unclear. A field experiment was conducted from 2018 to 2020 in the arid region of northwestern China to investigate the accumulation and distribution of dry matter and yield performance of wheat/maize intercropping in response to N-fertilizer postponed topdressing application. There were three N application treatments (referred as N1, N2, N3) for maize and the total amount were all 360 kg N ha⁻¹. N fertilizer were applied at four time, i.e. prior to sowing, at jointing stage, at pre-tasseling stage, and at 15 days post-silking stage, respectively. The N2 treatment was traditionally used for maize production and allocations subjected to these four stages were 2:3:4:1. The N1 and N2 were postponed topdressing treatments which allocations were 2:1:4:3 and 2:2:4:2, respectively. The results showed that the postponed topdressing N fertilizer treatments boosted the maximum average crop growth rate (CGR) of wheat/maize intercropping. The N1 and N2 treatments increased the average maximum CGR by 32.9% and 16.4% during the co-growth period, respectively, and the second average maximum CGR was increased by 29.8% and 12.6% during the maize recovery growth stage, respectively, compared with the N3 treatment. The N3 treatment was superior to other treatments, since it increased the CGR of intercropped wheat by 44.7% during the co-growth period and accelerated the CGR of intercropped maize by 29.8% after the wheat had been harvested. This treatment also increased the biomass and grain yield of intercropping by 8.6% and 33.7%, respectively, compared with the current N management practice. This yield gain was primarily attributable to the higher total translocation of dry matter. The N1 treatment increased the transfer amount of intercropped wheat by 28.4% from leaf and by 51.6% from stem, as well as increased the intercropped maize by 49.0% of leaf, 36.6% of stem, and 103.6% of husk, compared to N3 treatment, respectively. Integrated the N fertilizer postponed topdressing to the wheat/maize intercropping system have a promotion effect on increasing the translocation of dry matter to grain in vegetative organs. Therefore, the harvest index of intercropped wheat and maize with N1 was 5.9% and 5.3% greater than that of N3, respectively. This demonstrated that optimizing the management of N fertilizer can increase the grain yield from wheat/maize intercropping via the promotion of accumulation and translocation of dry matter.

The ever-growing population brings unprecedented challenges for agricultural production1. How to raise productivity and simultaneously ensure food security on the premise of environment friendliness is a thought-provoking issue. Intercropping, cultivating two or more crop species simultaneously on the same field2, is practiced widely throughout the world and considered to be an environment friendly system, as well as serve as a sustainable agricultural production system3–5. The primary reason that there are advantages to intercropping depends on the efficient use of light, nutrients, water, and other resources6,7. Research had revealed that the input of nitrogen fertilizer is the primary advantage of intercropping8,9. However, the application of a large amount of N causes
Crop growth rate (CGR) of intercropping system. The crop growth rate (CGR) of wheat/maize intercropping system followed an obvious double-peak curve in 2018–2020 (Fig. 1). In early growth stage, there was no difference between three N-fertilizer postponing application treatments. With the growth stage development, the CGR increased markedly and reached a maximum before wheat harvest. At this stage, the averaged CGR of IN1 and IN2 treatment was 32.9% and 16.4% higher than IN3 treatment. Then the CGR decreased with wheat harvest and 20 day intervals after wheat harvest. Error bars indicates standard error of the means (n = 3). Arrows labeled Hw indicates wheat harvest time.

Results
Crop growth rate of intercropping system. The crop growth rate (CGR) of wheat/maize intercropping system with different N management practices in 2018–2020. I, intercropping. N1, N2, and N3 represent N-fertilizer applied at 51, 72, and 93 kg N ha−1 as first top-dressing plus 63, 42, and 21 kg N ha−1 at third top-dressing, respectively. Plant sampling time is 15 day intervals before wheat harvest and 20 day intervals after wheat harvest. Error bars indicates standard error of the means (n = 3). Arrows labeled Hw indicates wheat harvest time.

many problems in today's agricultural production. It is desirable to study effective theory and technology to increase food production while reducing the application of high levels of N.

The technology of reducing nitrogen application primarily includes adjusting the management of nitrogen10, optimizing cropping systems11, applying new slow/controlled fertilizers12, integrating water and fertilizer13, and applying soil conditioners14. Among them, optimizing the management of N in intercropping systems is a feasible technology to satisfy the requirement to decrease the application of N, while simultaneously increasing yield. Optimizing the management of N, designated N-fertilizer postponed topdressing, can meet the demand of maize for N to produce high yields and increase the N use efficiency15,16. Similarly, when applied to cereal/legume intercropping, this strategy can boost crop productivity by retarding the “inhibitory effect of N application on N2 fixation” by cereal crops17 and optimizing the intraspecific relationships18,19. Cereal/cereal intercropping, such as wheat/maize strip intercropping, is a long-established stable production system in northwestern China. In this system, the late-maturing crop requires more nutrients to recover its growth to eliminate the competition from crops that mature early. The use of sufficient N for the late-growth stage of cereal crops can boost the recovery growth of late-maturing crops after the harvest of species that mature early, thereby, increasing the aboveground biomass and producing a high grain yield20. However, a shortage of N during this time period will inhibit reproductive and vegetative development, depress the accumulation and translocation of dry matter, and lead to a decrease in yield21,22. Therefore, adequate N for the crop late-growth stage is essential and conducive to the accumulation of dry matter and formation of grain. It is critical that the optimization of management of N fertilizer be based on the stage of crop growth to simultaneously meet the nutrient requirements of each crop and increase the intercropping yield.

Research has shown that the accumulation and translocation of dry matter can be used to measure cultivation technologies23,24. The grain yield is commonly directly related to the transportation of photosynthetic products that are stored in vegetative organs to the reproductive organs25,26. Tillage27, irrigation2, row ratio24, and the management of N fertilizer28,29 are those measures that affect dry matter. Among them, the management N fertilizer can directly affect the efficiency of leaf photosynthetic, thus, influencing the accumulation and translocation of dry matter30. However, to our knowledge, there has been no systematic research on the transportation of photosynthetic products that have been influenced by N fertilizer postponed topdressing technology. There is a lack of effective theoretical and practical bases to improve photosynthetic products during the practice of production using this technology.

To address the aforementioned issues, a field experiment with wheat/maize intercropping was conducted to explore the effects of postponed topdressing application of N fertilizer on the distribution of dry matter and yield performance. The objectives were to (i) quantify the yield and crop growth rate of wheat and maize, (ii) determine the contribution of photosynthetic products to grain, and (iii) reveal the mechanism of yield increases through the translocation of dry matter. Our study hypothesized that the application of N fertilizer postponed topdressing to wheat/maize intercropping can increase the accumulation of photosynthesis products, improve the translocation of dry matter, and boost system productivity.
Crop growth rate of wheat. The average CGR of wheat was significantly affected by cropping system, N-fertilizer treatment, and the two factors’ interaction effect (except from early to end of May and early to end of Jul). The 3-year average CGR of intercropped wheat was higher than sole wheat in whole growth period. There was no difference between each treatment at early growth stage but this trend changed with the growth stage developed (Fig. 2). The CGR of wheat increased rapidly and reached a maximum value when wheat was at early grain-filling stage. At this stage, intercropping significantly increased it by 13.4–57.9%, 6.0–60.9% and 13.5–62.5% than sole system in 2018, 2019 and 2020, respectively. The IN1 and IN2 treatment increased it of intercropped wheat by 44.7% and 22.7% compared with IN3 treatment. At late growth stage, the CGR of wheat with IN1 and IN2 was 58.3% and 30.7% higher than IN3 treatment.

Crop growth rate of maize. The average CGR of maize was significantly affected by cropping system and N-fertilizer postponing application, but the two factors’ interaction effect had no influence. The growth of intercropped maize was influenced by component wheat (Fig. 3). Before wheat harvest, the CGR of maize in sole cropping was higher than that in intercropping. The SN1-m and SN2-m treatments increased average CGR of sole maize by 15.6–40.9% and 9.0–21.6% compared with SN3-m treatment. After wheat harvest, the CGR of intercropped maize was higher than sole maize. The maximum CGR of maize was occurred at the end of July to middle of August, i.e., at anthesis to early grain filling stage. At this stage, the average CGR of intercropped maize under IN1 and IN2 treatments was increased by 29.8% and 12.6% compared with IN3 treatment. At the final sampling time, the IN1 and IN2 treatments improved the CGR of maize by 56.6% and 15.9% under intercropping, and by 41.6% and 12.4% under sole cropping, compared with IN3 treatment.

Biomass yield of wheat and maize. The biomass yield (BY) was significantly affected by cropping system, N-fertilizer treatment, and their interaction. On average of 3 years, the BY of intercropped wheat was 35.9–48.7% higher than that of sole wheat. The BY of intercropped maize was 12.8–31.1% higher than that of sole maize. Furthermore, the BY in intercropping was 24.7–32.9% higher than the weighted means of sole cropping (Fig. 4). For N treatment, the BY of intercropped wheat with IN3 was 28.7% and 14.1% lower than IN1 and IN2. Similarly, the BY of intercropped maize was 25.6% and 11.3% lower with IN3 compared to IN1 and IN2.

Distribution characteristics on aboveground dry matter of wheat. The transfer amount (DTA), transfer rate (DTR), and contribution rate to grain yield (GCR) of wheat during three experimental years were significantly influenced by cropping system, but not by N treatment and their interaction (Table 1). On average, intercropping increased DTA of leaf by 65.0%, DTR by 28.2%, and GCR by 69.3% compared with sole wheat. Similarly, the DTA, DTR, and GCR of intercropped wheat were increased by 89.5%, 60.6%, and 84.6% from stem, respectively. The IN1 treatment increased the DTA of intercropped wheat by 28.4%, DTR by 8.1%, and GCR by 29.6% from leaf, compared with IN3 treatment. Similarly, the DTA, DTR, and GCR were increased by 51.6%, 34.1%, and 55.0% from stem, respectively. Furthermore, the IN3 treatment increased the DTA of intercropped wheat by 10.7%, DTR by 3.4%, and GCR by 11.6% from leaf, and by 14.9%, 10.6%, and 19.9% from stem, compared with IN3 treatment.

Distribution characteristics on aboveground dry matter of maize. The DTA, DTR, and GCR of maize were significantly influenced by the cropping system and N treatment, but not by their interaction (Table 2). On average, intercropping increased the DTA by 38.7%, DTR by 29.1%, and GCR by 53.6% from leaf, compared with sole maize. Similarly, DTA, DTR, and GCR were increased by 27.4%, 20.4%, and 40.6% from stem, and by 51.4%, 61.2%, and 64.5% from husk, respectively. In wheat/maize intercropping, the IN1 treatment increased the DTA of leaf by 49.0%, DTR by 32.6%, and GCR by 48.4% compared to IN3 treatment. Similarly,
DTA, DTR, and GCR were increased by 36.6%, 8.6%, and 39.1% from stem, and increased by 103.6%, 36.8%, and 105.7% from husk, respectively. In addition, the IN2 treatment increased the DTA, DTR and GCR by 19.1%, 13.2%, and 12.6% from leaf, 14.3%, 5.3%, and 10.6% from stem and 43.6%, 19.7%, and 36.1% from husk compared with IN3 treatment.

Grain yield of wheat and maize. Copping system and N treatment individually had a significant effect on grain yield (GY) of wheat and maize in each year, and their interaction did as well (Fig. 5). It was consistent that crops in the intercropping system had yield advantages compared to corresponding sole crops. The GY in intercropping was 19.1–30.7% higher than the weighted means of sole cropping. In intercropping system, IN1 and IN2 increased the mixed yield by 33.3% and 18.0% in 2018, 34.1% and 14.9% in 2019, and 33.8% and 15.0% in 2020, compared with IN3 treatment, and IN1 treatment exhibited the most significant effect in improving grain yield. The GY of sole maize with SN1-m and SN2-m were 42.1% and 19.9% greater than SN3-m in 2018, 28.9% and 18.0% in 2019, and 33.0% and 8.9% in 2020.

Land use efficiency. The total LER of the wheat/maize intercropping was greater than 1.0 (Fig. 6). On average, the LER under N1 treatment was 6.6% and 7.0% higher than N2 and N3 treatments, respectively. Meantime, the LER of N1 treatment was 7.0% higher than N3 treatment.

Figure 3. Crop growth rate of maize in sole and intercropping systems in 2018–2020 with different cropping system and N management system. I, intercropping, S, sole cropping. For intercropping system, N1, N2, and N3 represent N-fertilizer applied at 51, 72, and 93 kg N ha⁻¹ as first top-dressing plus 63, 42, and 21 kg N ha⁻¹ at third top-dressing, respectively. For sole maize, N1, N2 and N3 represent N-fertilizer applied at 36, 72, and 108 kg N ha⁻¹ as first top-dressing plus 108, 72, and 36 kg N ha⁻¹ at third top-dressing, respectively. Plant sampling time is 15 day intervals before wheat harvest and 20 day intervals after wheat harvest. Error bars indicates standard error of the means (n = 3).
Yield components of wheat. The yield components are significant factors for achieving high yield of crops. Cropping system had a significant influence on spike number (SN) and thousand-kernel weight (TKW) of wheat, but not by N management and their interaction (Table 3). The SN of intercropped wheat was 11.9–25.2% higher than that of sole wheat under the same land area. Similarly, the KNS of intercropped wheat was 5.4–18.3% higher than sole wheat. Whereas, the TKW were 6.9–14.7% lower than sole wheat. The SN with the IN1 and IN2 were increased by 11.9 and 4.5%; KNS were increased by 16.0% and 10.0%; and TKW were increased by 7.3% and 3.2%, compared with IN3, respectively.

Yield components of maize. The SN and TKW of maize were significantly affected by cropping system, but not by N management and their interaction (Table 4). The SN of intercropped maize was 6.5–15.7% higher than that of sole maize under the same land area. Similarly, the KNS and TKW of intercropped maize were higher than sole maize. However, the TKW were lower than sole maize. The SN with the IN1 and IN2 were increased by 11.9 and 4.5%; KNS were increased by 16.0% and 10.0%; and TKW were increased by 7.3% and 3.2%, compared with IN3, respectively.

Table 1. Dry matter translocation and contribution rate to grain yield of leaf and stem in wheat in intercropping and sole cropping systems under different N management. Means with the same lowercase letters in the same column are significantly different at $P \leq 0.05$. a Intercrop and sole crop means the intercropped wheat and sole wheat. b For intercropping system, N1, N2, and N3 represent N-fertilizer applied at 51, 72, and 93 kg N ha$^{-1}$ as first top-dressing plus 63, 42, and 21 kg N ha$^{-1}$ at third top-dressing, respectively. For sole cropping, N1 represents N-fertilizer applied at 108 kg N ha$^{-1}$ as base fertilizer at sowing plus 72 kg N ha$^{-1}$ top-dressed at pre-tasseling. c DTA is transportation amount of dry matter in vegetative organ (kg); DTR is transfer rate of dry matter in vegetative organ (%); GCR is contribution rate of vegetative organs to grain (%).

| Year | Cropping system | N management practice | Leaf | Stem |
|------|-----------------|-----------------------|------|------|
|      | IN1 | IN2  | IN3  | SN1-w | DTA/kg | DTR/% | GCR/% | DTA/kg | DTR/% | GCR/% |
| 2018 | Intercrop | 1823a | 1598ab | 1508ab | 810d | 34.2f | 11.9bc | 1350a | 15.1ab | 14.2ab |
|      | Sole crop | 1845a | 1620ab | 1440ab | 1148bcd | 45.4de | 11.6bc | 743bcd | 7.8e | 6.2e |
| 2019 | Intercrop | 1594ab | 1321bc | 1151bcd | 851cd | 42.1ef | 8.4c | 1350a | 15.1ab | 14.2ab |
|      | Sole crop | 1321bc | 1084ab | 950abc | 851cd | 42.1ef | 8.4c | 120ab | 13.6ab | 10.0bcd |

Significance (p value)
- Cropping system (C): 0.000
- N management practice (N): 0.092
- C × N: 0.082

Figure 4. Biomass yield of wheat and maize with different N management practices under various cropping systems. I, intercropping, S, sole cropping. For intercropping system, N1, N2, and N3 represent N-fertilizer applied at 51, 72, and 93 kg N ha$^{-1}$ as first top-dressing plus 63, 42, and 21 kg N ha$^{-1}$ at third top-dressing, respectively. For sole maize, N1, N2, and N3 represent N-fertilizer applied at 36, 72, and 108 kg N ha$^{-1}$ as first top-dressing plus 108, 72, and 36 kg N ha$^{-1}$ at third top-dressing, respectively. For sole wheat, N1 represents the N-fertilizer applied at 108 kg N ha$^{-1}$ as base fertilizer at sowing plus 72 kg N ha$^{-1}$ top-dressed at pre-tasseling. Different lowercase above bars indicates significant difference ($P \leq 0.05$) among different N managements. Error bars indicates standard error of the means ($n = 3$).
Table 2. Dry matter translocation and contribution rate to grain yield of leaf, stem, and husk in maize of intercropping and sole cropping systems under different N management. Means with the same lowercase letters in the same column are significantly different at $P \leq 0.05$. a Intercrop and sole crop means the intercropped maize and sole maize. b For intercropping, N1, N2, and N3 represent N-fertilizer applied at 51, 72, and 93 kg N ha$^{-1}$ as first top-dressing plus 63, 42, and 21 kg N ha$^{-1}$ at third top-dressing, respectively. For sole cropping, N1, N2 and N3 represent N-fertilizer applied at 36, 72, and 108 kg N ha$^{-1}$ as first top-dressing plus 108, 72, and 36 kg N ha$^{-1}$ at third top-dressing, respectively. c DTA is transportation amount of dry matter in vegetative organ (kg); DTR is transfer rate of dry matter in vegetative organ (%); GCR is contribution rate of vegetative organs to grain (%).

| Year | Cropping system | N management practice | Leaf | Stem | Husk |
|------|----------------|----------------------|------|------|------|
|      |                |                      | DTA/kg | DTR/% | GCR/% | DTA/kg | DTR/% | GCR/% | DTA/kg | DTR/% | GCR/% |
| 2018 | Intercrop      | IN1                  | 1371abc 27.7ab 8.04ab  2116a 12.4ab 990a 21.0abc 5.79a | | | | | | | |
|      |                | IN2                  | 1177cde 25.1abc 6.28cdef 1869abc 10.0abc 786abc 19.9abcd 4.19abc | | | | | | | |
|      |                | IN3                  | 998efg 21.4bcde 6.16cdef 1528cdef 9.5abc 530cdef 16.2bcde 3.28bed | | | | | | | |
|      | Sole crop      | SN1 in              | 1293bcd 24.7abc 6.87cde 1701bcd 9.0bcde 888abc 19.8abc 4.71ab | | | | | | | |
|      |                | SN2 in              | 935gh 18.7cde 4.94cdef 1458cdef 7.9cde 564cde 14.5cdef 3.12bed | | | | | | | |
|      |                | SN3 in              | 630gh 13.7cde 3.10gh 1286ef 6.7de 353efg 10.8f 1.73def | | | | | | | |
| 2019 | Intercrop      | IN1                  | 1471ab 28.9a 7.80abc 2317a 28.6a 12.2ab 911ab 18.0abcde 4.82ab | | | | | | | |
|      |                | IN2                  | 1097def 21.9abc 5.39cdef 1915abcd 28.1a 9.5abcd 516cdef 13.7def 2.53cde | | | | | | | |
|      |                | IN3                  | 960gfh 19.0bcde 4.60efgh 1781bcd 8.6bcde 266fg 9.55fg 1.28ef | | | | | | | |
|      | Sole crop      | SN1 in              | 1156cde 22.4abc 4.33efgh 1961abc 23.3abcd 7.6cde 550cdef 14.0cdef 2.08def | | | | | | | |
|      |                | SN2 in              | 905gh 19.1cde 4.94defg 1458cdef 7.0cde 452def 12.1ef 1.92def | | | | | | | |
|      |                | SN3 in              | 533h 12.6a 1.94gh 1288ef 18.0d 117g 3.58g 0.42fg | | | | | | | |
| 2020 | Intercrop      | IN1                  | 1593a 27.9ab 9.04ab 2341a 24.2abcd 13.5a 938ab 24.6a 5.6a | | | | | | | |
|      |                | IN2                  | 1271cde 25.2abc 7.22abcd 1883abcd 10.9abc 701bcd 22.0ab 3.98abc | | | | | | | |
|      |                | IN3                  | 1018efg 22.5abc 6.00cdefg 1650cdef 9.4abcd 598cdef 20.7abcd 3.30bcd | | | | | | | |
|      | Sole crop      | SN1 in              | 1180def 23.3abc 7.25abcd 1715bcd 10.9abc 525cdef 12.1ef 3.41cde | | | | | | | |
|      |                | SN2 in              | 835gh 19.5bcde 4.36efgh 1406cdef 7.5cde 450def 11.2ef 2.95cde | | | | | | | |
|      |                | SN3 in              | 710gh 18.8cde 4.15efgh 1229f 20.4bcde 7.2cde 335efg 9.05fg 1.96def | | | | | | | |

Significance ($p$ value)

| Cropping system (C) | N management system (N) | C × N |
|---------------------|-------------------------|-------|
| 0.000               | 0.000                   | 0.000 |
| 0.000               | 0.000                   | 0.000 |
| 0.081               | 0.834                   | 0.469 |

Figure 5. Grain yield of wheat and maize in sole and intercropping systems as affected by N management practices in 2018–2020. I, intercropping, S, sole cropping. For intercropping system, N1, N2, and N3 represent N-fertilizer applied at 51, 72, and 93 kg N ha$^{-1}$ as first top-dressing plus 63, 42, and 21 kg N ha$^{-1}$ at third top-dressing, respectively. For sole cropping, N1, N2, and N3 represent N-fertilizer applied at 36, 72, and 108 kg N ha$^{-1}$ as first top-dressing plus 108, 72, and 36 kg N ha$^{-1}$ at third top-dressing, respectively. DTA is transportation amount of dry matter in vegetative organ (kg); DTR is transfer rate of dry matter in vegetative organ (%); GCR is contribution rate of vegetative organs to grain (%).
6.2–11.1% and 11.1–17.6% lower than sole maize. The SN of sole maize with the SN1-m and SN2-m were promoted by 8.5% and 7.0%, the KNS by 14.9% and 5.7%, and TKW by 5.7% and 3.5% compared with SN3-m treatment, respectively. The same trend was found in intercropping maize. The SN of intercropped maize under IN1 and IN2 were 24.8% and 15.5% higher than IN3, the KNS were 12.0% and 7.7%, and TKW were 11.9% and 9.5%, respectively.

Harvest index of wheat and maize. Harvest index (HI) of wheat and maize was significantly affected by cropping system and N-fertilizer treatment (except for wheat), but not by their interaction (Fig. 7). The HI of intercropped wheat with IN1 and IN2 were 5.9% and 2.6% greater than IN3, and of intercropped maize was 5.3% and 3.6% with IN1 and IN2 compared with IN3. The HI of sole maize with SN1-m and SN2-m was 6.9% and 3.9% higher than that of SN3-m. The HI of sole wheat was lowest, only reached to 0.40. Among the three N treatments, IN1 and IN2 increased the HI of intercropped wheat and maize.

Path analysis. The correlation coefficients between the grain yield and yield components were used to separate into direct and indirect effects via path analysis (Fig. 8A). The spike number (SN) and thousand-kernel weight (TKW) of wheat had the highest direct path coefficient and correlation coefficient than kernel number per spike (KNS). In addition, TKW had a positive indirect path coefficient with SN, and SN had a positive indirect path coefficient with TKW, indicating that yield was influenced by the interaction between them. Although

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**Table 3.** The spike number (SN), kernel number per spike (KNS), and thousand-kernel weight (TKW) of wheat in sole crop and intercrop as affected by cropping system and N management in 2018–2020. Means with the same lowercase letters in the same column are significantly different at \( P \leq 0.05 \). 

| Cropping systemsa | N management systemb | SN \( 10^7 \) (ha\(^{-1}\)) | KNS | TKW (g) |
|-------------------|----------------------|----------------|------|--------|
|                   |                      | 2018 | 2019 | 2020  | 2018 | 2019 | 2020  | 2018 | 2019 | 2020  |
| Intercrop         | IN1                  | 327b | 323b | 341b  | 22.0a | 38.6a | 35.8a  | 43.6ab| 42.9b | 44.8b  |
|                   | IN2                  | 308b | 298b | 320b  | 20.8a | 35.4b | 35.3a  | 42.0bc| 41.9b | 42.3c  |
|                   | IN3                  | 298b | 283b | 305b  | 18.0a | 33.5c | 31.6a  | 40.7c | 40.7b | 40.9c  |
| Sole crop         | SN1-a                | 623a | 603a | 655a  | 16.9a | 34.2bc| 29.2a  | 45.6a | 47.5a | 47.2a  |

**Figure 6.** Land use efficiency of wheat/maize intercropping systems under different N managements practices in 2018–2020. N1, N2, and N3 represent N-fertilizer applied at 51, 72, and 93 kg N ha\(^{-1}\) as first top-dressing plus 63, 42, and 21 kg N ha\(^{-1}\) at third top-dressing, respectively.
KNS has the lowest direct path coefficient (0.064), the indirect path coefficient of KNS to SN is −0.240, which is 3.75 times for its direct path coefficient.

The SN of maize was significantly correlated with grain yield (Fig. 8B). Furthermore, SN had the highest correlation coefficient than TKW and KNS, indicating SN had direct influence on grain yield. Nevertheless, KNS and TKW could indirectly affect grain yield via SN, with TKW contributing more than KNS.

**Discussion**

**The crop growth rate and biomass yield.** Numerous studies had reported one important factor affecting the obtain of grain yield was dry matter accumulation. This is mainly because dry matter accumulation and distribution in reproductive organs of crops, can reflect indirectly grain yield response to the availability of resource. In the present study, the CGR of wheat/maize intercropping presents an obvious double-peak curve in each studied year. Before wheat harvest, the CGR of intercropping reached the maximum value. After wheat harvest, it decreased and reached the second maximum value when maize was at early grain filling stage. The reason was that intercropped wheat was earlier planted and created a competitive advantage over the later planted intercropped maize for resources uptake during co-growth period, resulted in a strong suppression of intercropped maize. Thus, the CGR of the intercropped wheat was higher than sole wheat. Owing to the high

| Cropping systemsa | N management systemb | SN 10³ (ha⁻¹) | KNS | TKW(g) |
|------------------|---------------------|--------------|-----|-------|
|                  |                     | 2018 | 2019 | 2020 | 2018 | 2019 | 2020 | 2018 | 2019 | 2020 |
| Intercrop        | IN₁                 | 6.89c | 7.45bc | 7.06c | 564ab | 543ab | 472a  | 347abc | 362b  | 360b  |
|                  | IN₂                 | 6.06cd | 6.52c  | 6.00d  | 550ab | 517ab | 452a  | 334bc  | 356b  | 359ab |
|                  | IN₃                 | 5.17d  | 5.84c  | 5.61d  | 481c  | 479c  | 449a  | 310c   | 326c  | 320ab |
| Sole crop        | SN₁-m.              | 10.18a | 10.96a | 10.78a | 648a  | 565a  | 541a  | 394a   | 402a  | 393a  |
|                  | SN₂-m.              | 9.29a  | 10.15a | 9.39b  | 572ab | 551ab | 489a  | 389a   | 395a  | 381a  |
|                  | SN₃-m.              | 8.27b  | 9.27ab | 9.00b  | 551ab | 499ab | 475a  | 374ab  | 381ab | 370a  |

**Table 4.** The spike number (SN), kernel number per spike (KNS), and thousand-kernel weight (TKW) of maize in sole crop and intercrop as affected by cropping system and N management in 2018–2020. Means with the same lowercase letters in the same column are significantly different at \(P<0.05\). a Intercrop and sole crop means the intercropped maize and sole maize. b For intercropping, N₁, N₂, and N₃ represent N-fertilizer applied at 51, 72, and 93 kg N ha⁻¹ as first top-dressing plus 63, 42, and 21 kg N ha⁻¹ at third top-dressing, respectively. For sole cropping, N₁, N₂ and N₃ represent N-fertilizer applied at 36, 72, and 108 kg N ha⁻¹ as first top-dressing plus 108, 72, and 36 kg N ha⁻¹ at third top-dressing, respectively.

**Figure 7.** Harvest index of wheat and maize in sole and intercropping systems with different N management practices in 2018–2020. I, intercropping, S, sole cropping. For intercropping system, N₁, N₂, and N₃ represent N-fertilizer applied at 51, 72, and 93 kg N ha⁻¹ as first top-dressing plus 63, 42, and 21 kg N ha⁻¹ at third top-dressing, respectively. For sole maize, N₁, N₂ and N₃ represent N-fertilizer applied at 36, 72, and 108 kg N ha⁻¹ as first top-dressing plus 108, 72, and 36 kg N ha⁻¹ at third top-dressing, respectively. For sole wheat, N₁ represents the N-fertilizer applied at 108 kg N ha⁻¹ as base fertilizer at sowing plus 72 kg N ha⁻¹ top-dressed at pre-tasseling. Different lowercase above bars indicates significant difference \(P≤0.05\) among different N managements. Error bars indicates standard error of the means \((n=3)\).
light intensity, wheat (C3 crop) may use light more efficiently in the intercropping than in sole crop during co-growth period. The CGR of intercropped maize was lower than sole cropping before wheat harvest, but higher after wheat harvest. This result was consistent with previous studies, with aboveground dry matter of maize showing recovery growth after wheat harvest. Therefore, the weighted means of BY in intercropping was 24.7–32.9% higher than that of monocropping. That means the intercropping can accumulate more dry matter than the corresponding sole system.

In this study, IN1 and IN2 treatment, which postponed 20% and 10% of total N fertilizer from maize jointing stage to 15 days post-silking stage, had a significant effect on boosting the maximum CGR of intercropped wheat, which was boosted by 44.7% and 22.7% compared to IN3 treatment. That may because the IN3 treatment used excessive N fertilizer at maize jointing stage which is not suitable for intercropped wheat growing. Numerous studies have shown that nutrients play a crucial role in recovery growth of late-maturing crops after the early-maturing crops harvest. Compared to the IN3 treatment, the IN1 and IN2 treatment increased the CGR of intercropped maize by 29.8% and 12.6%. The reason might be the postponed topdressing N fertilizer greatly intensified the interspecific competition in co-growth period but eventually generated a substantial complementarity.

The transfer of vegetative products to ear. The proportion of photosynthetic products stored in leaves and stems is relatively small and most dry matter accumulation during the grain-filling period is accumulated in grain. In this study, intercropping had a significant effect on aboveground dry matter translocation. It increased DTA of leaf by 65.0%, DTR by 28.2%, and GCR by 69.3% and 89.5%, 60.6%, and 84.6% from stem compared with sole wheat, respectively. One main reason is that during the co-growth period, wheat has a competitive advantage, and can obtain more light and heat resources. Meantime, wheat shaded the adjacent maize, thus reducing solar radiation received by maize. Interspecific competition not only includes aboveground competition but also contains belowground competition. Belowground competition was mainly for growth space, water, and nutrients. As shown in this study, IN1 and IN2 treatments increased the DTA of intercropped wheat by 10.7–28.4%, DTR by 3.4–8.1%, and GCR by 11.6–29.6% from leaf, compared to IN3 treatment, and 14.9–51.6%, 10.6–34.1%, 19.9–55.0% from stem, respectively. Therefore, IN1 treatment showed the best effect on optimizing dry matter distribution of aboveground tissue in intercropped wheat. Previous research suggested that adequate N supply directly affects the production, partitioning, and translocation of dry matter. An increasing in wheat transferring amount, transferring rate, and contribution rate to grain might because wheat has a higher competitive ability for N. Intercropped wheat having much greater root length density, and roots spreading laterally into the maize strip during the co-growth period, and then competing for N from the adjacent maize strip.
However, late-maturing crops could form the compensatory effect of time and space when early-maturing crops were harvested. In this study, intercropping increased the DTA by 38.7%, DTR by 29.1%, and GCR by 53.6% from leaf compared to sole maize, by 27.4%, 20.4%, and 40.6% from stem, and by 51.4%, 61.2%, and 64.5% from husk, respectively. That means the increasing in maize aboveground dry matter translocation probably resulted from compensatory effect, which late-maturing crops (such as maize and soybean) root gradually expand to the underground space of early-maturing crops (like wheat) after it harvest, absorb more nutrient and water, thereby accelerated the growth rate of late-maturing crops. It has been confirmed that recovery growth is fundamentally related to the supplemental N. In wheat/maize intercropping, the IN1 treatment increased the DTA, DTR, and GCR by 49.0%, 32.6%, and 48.4% from leaf, by 36.6%, 8.6%, and 39.1% from stem, and by 103.6%, 36.8%, and 105.7% from husk compared to IN3 treatment, respectively. In this study, maize performed the highest compensatory intensity during the third recovery stage (i.e., from grain filling to maturity), which was similar to previous research. That is to say, suitable fertilizer N management at this stage is the key to enhance recovery growth. The IN1 treatment transferred 20% of total N at this stage can well match fertilizer N supply with crop N requirement.

Yield performance and yield components. The common advantages of intercropping are (i) efficient use of nutrients, light, and water, (ii) achieving agricultural biodiversity, and (iii) increasing yield. In northwest China, wheat/maize intercropping, an old cropping practice that aims to match efficient crop demands to the available growth resources and labor, has been widely used by farmers. In the present study, the grain yield in intercropping was 19.1–30.7% higher than the weighted means of corresponding sole cropping. It was because intercropped wheat had a strong competition relative to the accompanying maize, more resources in the available growth resources and labor, has been widely used by farmers. In the present study, the grain yield of intercropped wheat was 19.1–30.7% higher than the weighted means of corresponding sole cropping. It was because intercropped wheat had a strong competition relative to the accompanying maize, more resources in the adjacent vacant area were available to intercropped wheat, thus intercropped wheat obtained greater yield components and higher grain yield than sole wheat under the same area. After wheat harvest, expansion of absorption space for light, heat, and gas resources on the ground coupled with the expansion of absorption scope for water and nutrients underground gave intercropped maize a chance to compensate, which is the basis for high yields of intercropped maize. It has been discovered that favorable interspecific competition and compensation effect is beneficial to improve yield components and higher grain yield than sole wheat and maize. Under the same land area, intercropping with the three N fertilizer postoned topdressing treatment increased SN of wheat by an average 18.0% and by 11.2% of maize compared to sole cropping, across the 3 years. Similarly, intercropping increased KNS of wheat by 15.0%. This is mainly because favorable interspecific competition and compensation effect is beneficial to improve yield components and higher grain yield, thus obtaining the higher harvest index.

In present study, IN1 and IN2 treatments boosted the mixed yield by 33.7% and 15.9% compared with IN3 treatment. It had been reported that the N1 treatment, where 45 kg N ha−1 was applied at the first topdressing plus 135 kg N ha−1 at the third topdressing, can boost the grain yield of intercropped pea and maize compared to the N3 treatment which 135 kg N ha−1 was topdressing at the first plus 45 kg N ha−1 at the third topdressing. Mainly because the competitive ability of legumes was improved in planting mixtures so as to enhance the yield of intercropping. N application could not only boost the grain numbers per unit area, but also improve grain protein concentration. The IN1 and IN2 treatment increased the spike number (by 13.8 and 5.0%), kernel number per spike (by 16.0% and 10.0%), and the thousand-kernel weight (by 7.3% and 3.2%) of intercropped wheat; similarly enhanced the spike number (by 24.8% and 15.5%), the kernel number per spike (by 12.0% and 7.7%), and the thousand-kernel weight (by 11.9% and 9.5%) of intercropped maize, respectively. One reason for this phenomenon might be N-fertilizer postponed topdressing is an effective approach to match fertilizer N supply with crop N requirement which is crucial to achieving high productivity. Path analysis showed that grain yield of wheat was mainly derived from thousand-kernel weight, and while kernel number per spike indirectly influences spike number so as to affect the grain yield. The grain yield of maize was mainly derived from spike number, while thousand-kernel weight and while kernel number per spike indirectly influences spike number so as to affect the grain yield. In this experiment, IN1 and IN2 treatments increased the average HI of intercropped wheat by 5.9% and 2.6%, and by 5.3% and 3.6% of intercropped maize compared to IN3 treatment. This mainly because intercropped wheat can capture more resources during the co-growth stage and intercropped maize attributed to more transfer of aboveground dry matter to vegetative organs to ear during the late-growth stage. Furthermore, the total LER of wheat/maize intercropping averages 1.28, which indicated the intercropping system used less land but produced more grain than their corresponding monocultures. This means intercropping system can more efficiently use the resources to product than monocultures.

Conclusions

The N-fertilizer postponed topdressing treatments, which transferred 20% or 10% of the total amount N from the jointing stage to 15 days post-silking stage, boosted the crop growth rate of intercropping wheat during the co-growth stage and simultaneously accelerated the crop growth rate of intercropping maize crops during their recovery growth stage, respectively. They also increased the biomass yield of intercropping by 8.6% and 5.0%, compared with traditional N management practices, respectively. The N fertilizer postponed topdressing optimized the transfer of dry matter from vegetative organs to grain and increased the proportion postponed that boosted the amount of transportation. The postponed topdressing applications at 20% and 10% enhanced the mixed grain yield by 33.7% and 16.0%, compared with traditional N management practices, respectively. The harvest index of intercropped wheat increased by 5.9% and 2.6%, respectively, and that of intercropped maize by 5.3% and 3.6%, compared with traditional N management practices, respectively. Our results showed that N fertilizer postponed topdressing, particularly postponing the application at 20%, can increase the accumulation.
of photosynthetic products and optimize the translocation of dry matter, which improved the productivity of intercropping systems.

**Materials and methods**

**Test site description.** The field experiment was carried out in 2018–2020 at the Oasis Agricultural Trial Station (37°30′N, 103°5′E; 1776 m a.s.l.) of Gansu Agricultural University. The station is located in the eastern part of the Hexi Corridor of northwestern China. At experimental site, the average annual sunshine duration (1960–2009) was 2945 h, annual air temperature was 7.2 °C, and accumulated temperature (above 10 °C) was 2985 °C. In this region, the accumulated heat and light is abundant for one crop per year but insufficient for two, which is suitable for developing of intercropping. Wheat/maize intercropping, introduced to this region since the twentieth century, is still a prevailing cropping system44. The soil at the experimental site is classified as an Aridisol51. Before the experiment, soil properties of the top 0–30 cm soil layer were 8.0 pH (1:2.5 soil:water) using a pH meter, 11.3 g/kg soil organic carbon by the potassium dichromate heating oxidation-volumetric method, 1.44 g/cm3 soil bulk density by cutting ring method, 0.94 g/kg total N by Elementar (Vario MACRO cube, Germany), 29.2 mg/kg available phosphorous (P; Olsen-P) by the molybdenum-blue method, and 152.6 mg/kg available potassium (K; NH4OAc-extractable-K) by NH4OAc soaking method.

**Experimental design.** The experimental design was a factorial design with seven treatments and three replications. Cropping systems were sole maize, sole wheat, and wheat/maize intercropping. Three N-fertilizer postponed top-dressing treatments (N1, N2 and N3) were designed according to key growth stage of maize that was jointing stage (V6), pre-tasseling stage (V12), and 15 days post-silking (R2) (Fig. 9). The N3 treatment is the local N management practice in this region. N fertilizer rate for sole maize was 360 kg N ha−1, in which 20% and 40% of total N application were applied pre-plant and top-dressed at pre-tasseling stage, respectively. The remaining 40% was divided into jointing stage and 15 days post-silking stage and the allocations were, respectively: 10% and 30% for N1; 20% and 20% for N2; and 30% and 10% for N3, thus formed postponing application of 20% (N1), 10% (N2), and without postponing application (N3). The total amount of N fertilizer was 285 kg N ha−1 for wheat/maize intercropping, which was calculated by the bandwidth ratio. N fertilizer rate for sole wheat was 180 kg N ha−1, in which 108 kg N ha−1 was base applied at sowing and 72 kg N ha−1 at booting stage (i.e. pre-tasseling stage of maize). Crops in sole and intercropping received an equivalent N rate at specific area. The detailed treatment code and N-fertilizer management were presented in Table 5. The amount of phosphorus was 180 kg P ha−1 and applied in all plots before sowing. The types of N and P were urea (46–0–0, N–P–K) and superphosphate (11–51–0) fertilizers. The topdressing fertilizer in maize strips was achieved by the drip irrigation method.

The plot size for intercropping was 5.7 m length × 6 m width, and for sole cropping was 6 m length × 6 m width, with every neighboring plot had a 50 cm wide by 30 cm high ridge built to eliminate potential water movement. In intercropping plots, wheat and maize were alternated in 190 cm wide strips, in which, wheat strip was 80 cm wide consisting of six rows with a row space of 12 cm, and maize strip was 110 cm wide consisting of three rows with 40 cm row (Fig. 10). Thus, in the wheat/maize intercropping, wheat account for 42% of the plot area and maize account for 58%. The planting density of sole wheat was 6,750,000 plants ha−1. For each crop, the same area-based planting density was employed in intercropping and sole cropping. Intercropped wheat was at 2,840,000 plants ha−1 and sole maize was at 52,000 plants ha−1. Field maize (cv. Xian-yu 335) was planted on 22 April 2018, 22 April 2019 and 20 April 2020, and harvested on 25 September 2018, 22 September 2019 and 25 September 2020. Wheat (cv. Ning-chun 2) was sown on 16 March 2018, 17 March 2019 and 17 March 2020 and harvested on July 27, 24 and 27 in 2018, 2019 and 2020. The use of maize and wheat seeds in the present study was permitted by Gansu Agricultural University and it complies with local and national guidelines and legislation. Maize was mulched by plastic film (polyethylene film 0.01 mm thick and 120 cm wide), which made in Lanzhou Green Garden Corporation of China, Lanzhou. It is an innovative technology largely adopted in arid areas to improve maize productivity52. There is low precipitation at the testing areas (< 155 mm annually), so that supplemental irrigation was applied. Before soil freezing, 120 mm of
irrigation was applied to all plots. Total amount of irrigation was 240 mm for sole wheat, 405 mm for sole maize and 480 mm for intercropping during each growing season. Other agronomic practices, except for the fertilizer application, were kept uniform in this study.

### Plant sampling and analysis

#### Aboveground dry matter

The sole and intercropped components were collected for aboveground dry matter determination at 15 days intervals before wheat harvest, and at 20 days intervals after wheat harvest. The first sampling was conducted at 15 days after maize emergence. For the sake of minimizing the influence of destructive sampling on yield formation, 2/3 of the plot in width was used to measure dry matter accumulation, and the remaining 1/3 were used to measure grain yield at physiological maturity. At each sampling date, 20 wheat plants in the same row were randomly selected to determine wheat aboveground dry matter (DM). For maize, 10 individual plants were randomly selected before jointing stage and 5 plants after jointing stage to determine maize DM.

Samples were separated into leaf, stem, and ear of wheat and leaf, stem (include sheath), husk, and ear of maize per plant. All samples were oven-dried at 105 °C for 30 min and weighed after further drying at 80 °C until a constant weight was attained. Finally, the aboveground biomass was used to calculate the transportation amount, and transportation rate of dry matter in vegetative organs to grain, and the contribution rate of vegetative organs to grain according to Yin.

The equation was following:

\[
D_T = \frac{D_T}{D_W} \times 100\% \tag{2}
\]

### Table 5. N fertilizer allocation amount (kg ha\(^{-1}\)) and percentage in each treatment

| Cropping systems | N management system\(^a\) | Base N fertilizer\(^b\) | Top-dressing of N fertilizer | Postponed percentage\(^c\) | N fertilizer Total |
|------------------|--------------------------|------------------------|----------------------------|--------------------------|------------------|
| Wheat/maize intercropping | IN\(_1\) | 88 | 51 | 83 | 63 | 20 | 285 |
|                  | IN\(_2\) | 88 | 72 | 83 | 42 | 10 | 285 |
|                  | IN\(_3\) | 88 | 93 | 83 | 21 | - | 285 |
| Sole maize       | SN\(_1\) | 72 | 36 | 144 | 108 | 20 | 360 |
|                  | SN\(_2\) | 72 | 72 | 144 | 72 | 10 | 360 |
|                  | SN\(_3\) | 72 | 108 | 144 | 36 | - | 360 |
| Sole wheat       | SN\(_1\) | 108 | 72 | 0 | 0 | - | 180 |

For sole maize, N\(_1\), N\(_2\) and N\(_3\) represent N-fertilizer applied at 36, 72, and 108 kg N ha\(^{-1}\) as first top-dressing plus 108, 72, and 36 kg N ha\(^{-1}\) at third top-dressing, respectively. For sole wheat, N\(_1\) represents the N-fertilizer applied at 108 kg N ha\(^{-1}\) as base fertilizer at sowing plus 72 kg N ha\(^{-1}\) top-dressed at pre-tasseling. Intercropped components (i.e., maize and wheat) received the same area-based N fertilizer rate as the corresponding sole crops. The postponed percentage applied only for maize.

![Diagram of wheat/maize intercropping](image)

**Figure 10.** Information of (a) the spatial arrangement of wheat/maize intercropping with wheat strip of 80-cm (six rows) alternated with maize strip of 110-cm (three rows) and (b) the field planting diagrammatic representation of wheat/maize intercropping at Wuwei experimental station in northwestern China.
where DTA (kg ha\(^{-1}\)) represents transportation amount of dry matter in vegetative organ, LDW (kg ha\(^{-1}\)) represents the largest dry weight of the vegetative organ, DWM (kg ha\(^{-1}\)) represents the dry weight of the same vegetative organ in maturity, DTR represents transfer rate of dry matter in vegetative organ (%), GCR represents contribution rate of vegetative organs to grain (%) and GDW (kg ha\(^{-1}\)) represents the dry weight of grain.

**Crop growth rate.** The crop growth rate was calculated (CGR) (kg ha\(^{-1}\) day\(^{-1}\)) using the following equation:

\[
\text{CGR} = \frac{W_2 - W_1}{T_2 - T_1} \times 100\%
\]

where \(W_2\) and \(W_1\) are the aboveground biomass accumulation sampled at \(T_2\) and \(T_1\).

**Grain yield, biomass yield, yield components, and harvest index.** Grain yield (GY) and biomass yield (BY) were measured after air-drying, cleaning of the sole and intercropped systems from all plots. At the maturity stage, 30 wheat plants and 10 maize plants in the undisturbed natural strip were randomly selected to test kernel number per spike (KNS) and thousand-kernel weight (TKW); measure 2.5 \(\times\) 0.8 m = 2 m\(^2\) (wheat), 5 \(\times\) 1.0 m = 5 m\(^2\) (maize) square area to count the spike number (SN) and calculate the grain yield per unit area by threshing and weighing. Harvest index (HI) was determined by dividing GY by aboveground BY at physiological maturity:

\[
\text{HI} = \frac{\text{GY}}{\text{BY}}
\]

**Land use efficiency.** The land equivalent ratio (LER) was calculated as follows:

\[
\text{LER} = \frac{Y_{im} + Y_{sw}}{Y_{sm} + Y_{iw}}
\]

where \(Y_{im}\) and \(Y_{sm}\) are the grain yield of intercropped maize and sole maize, respectively, and \(Y_{iw}\) and \(Y_{sw}\) are the grain yield of intercropped wheat and sole wheat, respectively. A value of LER > 1.0 indicates a yield advantage of intercropping over sole cropping and vice versa.

**Statistical analysis.** Data were analyzed at \(P<0.05\) level using Statistical Analysis Software (SPSS software, 21.0, SPSS Institute Ltd, Chicago, USA). Analysis of variance was conducted by using Duncan’s multiple range tests at \(P<0.05\) level to test for the significance of cropping system, N-fertilizer postponed topdressing effects, and their interactions.

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Author contributions
Q.C., F.H., Z.F., and W.Y. designed the experiments. K.X. conducted the field experiment and collected all data in study years. K.X. was involved in the data interpretation and wrote the whole paper. Q.C. and F.H. critically revised this manuscript. All authors reviewed the final manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to Q.C.

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