agronomy

Article

Does Belt Uniform Sowing Improve Winter Wheat Yield under High Sowing Density?

Mei Chen [1], Yong-He Zhu [2], Ming-Jian Ren [1], Long Jiang [1], Jin He [1,*] and Rui Dong [3]

1 College of Agriculture, Key Laboratory of Plant Resource Conservation and Germplasm Innovation in Mountainous Region (Ministry of Education), Guizhou University, Guiyang 550025, China
2 College of Agriculture, Nanjing Agricultural University, Nanjing 210095, China
3 College of Zoology, Guizhou University, Guiyang 550025, China
* Correspondence: jhe5@gzu.edu.cn

Abstract: The belt uniform (BU) sowing pattern can improve the yield of winter wheat, but whether and how the BU sowing pattern can increase yield under different sowing densities is unknown. The field study was conducted in Guiyang (Guizhou province) during the growing season in 2017–2018, 2018–2019, and 2019–2020. Four winter wheat cultivars were used in field experiments to investigate the changes of the dry matter accumulation and partition, yield and yield components at maturity under five sowing densities (75, 150, 225, 300, and 375 plants per m^2), and three sowing patterns: line and dense (LD) sowing with 33.3 cm row spacing (LDS); the belt uniform (BU) sowing with 15 cm (BUN), and 20 cm (BUW) row spacing. The BU sowing pattern significantly increases shoot dry matter and grain yield in all four winter wheat cultivars under all five sowing densities and in each growing season, particularly under the high sowing density of 300 and 375 plants m^{-2}. Harvest index was unaffected by the different sowing densities and sowing patterns. While spike number increased, grain weight per spike decreased with the increase in sowing density. The 1000-grain weight and grain number per spike were unaffected by the sowing patterns. The variation in the shoot dry weight can explain 94% variation in grain yield and 66% variation in spike number. Allometric analysis showed that more dry matter was partitioned to the spike than to the stem and leaf. We conclude that the BU sowing pattern can increase grain yield under high sowing densities associated with a high shoot dry matter accumulation and its partition to the spike.

Keywords: dry matter accumulation; allometric growth; harvest index; yield components

check for updates

Citation: Chen, M.; Zhu, Y.-H.; Ren, M.-J.; Jiang, L.; He, J.; Dong, R. Does Belt Uniform Sowing Improve Winter Wheat Yield under High Sowing Density? *Agronomy* **2022**, *12*, 2936. https://doi.org/10.3390/agronomy12122936

Academic Editor: Meisam Zargar

Received: 22 October 2022
Accepted: 18 November 2022
Published: 23 November 2022

1. Introduction

Wheat is a main cereal crop grown worldwide [1], and is the third most important staple crop in China. More than 15% of wheat yield is needed to fulfill the wheat demand being driven by the increases in the population and diet changes by 2030 in China [2]. The reducing of the arable land area and changing of the climate and environmental degradation [3–6], which limited productivity and increasing of the food supply, was largely dependent on the high-yield breeding strategies [7] and development of the new agronomic practices, such as sowing patterns [8,9] and optimal sowing density [10,11].

Sowing pattern is an important factor in sustainable agriculture, as it influences plant distribution in the field, which in turn affects the functional traits related to photosynthesis, growth, and yield [12,13]. Raised-bed sowing can increase wheat and rice yield [14–16], and furrow sowing can increase the yields of winter wheat [17]. A wide-precision planting pattern, with 6–8 cm sowing width can also increase winter wheat yield [18]. Our previous study showed that the belt uniform (BU) sowing pattern could significantly increase the winter wheat yield [8]. Thus, development the new sowing patterns made a great contribution to the yield improvement. Previous studies showed new sowing methods could increase the yield by increasing the spike number (SN) per m^2 [18,19] and biomass [8,20,21].

Biomass accumulation is essential for the yield formation, as more biomass partition to the grain can achieve high yield [22,23]. However, the spike growth related to the stem and leaf and its roles in yield performance were not known under different sowing patterns.

Apart from the sowing pattern, the appropriate sowing density is also a very important factor determining grain yield. Optimal sowing density depends on the variety, soil type, precipitation, and soil nutrients [10,24,25]. Sowing density is a determinative factor for winter wheat grain yield and varies with the sowing pattern [26,27], which is associated with the changing of the inter- and intra-plant competition for nutrition, water, and light nutrients for crop growth, resulting in the variation in the grain yield [28], particularly under excessively high density [29]. Previous studies showed the crop yield response curvilinear to sowing density, reaching a maximum at the optimal sowing density [30,31]. Thus the yield response and the underlying mechanisms related to the yield performance were needed to investigate under different sowing patterns.

Previously, we showed that the belt uniform (BU) sowing pattern can improve the yield of winter wheat [8], but how the dry matter accumulation, partition to the grain, and grain yield responds to different sowing densities under the BU pattern is unknown. In this study, we aim to investigate the changes of the dry matter accumulation, partition to the grain and yield, and yield components under five sowing densities (75, 150, 225, 300, and 375 plants per m^2) and three sowing patterns (line and dense (LD) sowing with 33.3 cm row spacing (LDS); the belt uniform (BU) sowing with 15 cm (BUN), and 20 cm (BUW) row spacing). We hypothesized that (1) the belt uniform sowing pattern (BU) can increase winter wheat yield under high sowing density, (2) high dry matter accumulation is coordinated with high dry matter partition to the spike to increase the wheat yield at high sowing density.

2. Materials and Methods

A three-year field experiment was conducted in Guiyang, Guizhou province, China. The soil at the experimental site is yellow soil, according to the Chinese soil classification system. The soil organic matter is 6.60 g kg^{-1} and the available P, N, and K are 4.85 mg kg^{-1}, 31.50 mg kg^{-1}, and 141.69 mg kg^{-1}, respectively.

The experimental plot was 2 m wide and 2 m long; there were 6 rows in each plot. Three sowing patterns were adopted in this study, the line and dense (LD) sowing with 33.3 cm row spacing (LDS); the belt uniform (BU) sowing with 15 cm row spacing (BUN); and the BU with 20 cm row spacing (BUW (Figure 1). Four winter wheat cultivars, two common (Guinong 19 (G19) and Guinong 30 (G30)), and two containing high anthocyanin (about 50 mg kg^{-1}; Guizi 1 (G1) and Guizi 4 (G4)) released by Guizhou university were used in this study. The wheat cultivars were planted at five densities of 75, 150, 225, 300, and 375 plants per m^2. The sowing dates were 5 November 2017, 19 November 2018, and 23 November 2019, while the corresponding harvest dates were 11 May 2018, 18 May 2019, and 23 May 2020 for 2017–2018, 2018–2019, and 2019–2020 growing seasons. A completely randomized experimental design was used in this study and three plots were used for each cultivar, sowing density, and sowing pattern for a total of 180 plots (3 sowing patterns × 4 cultivars × 5 densities × 3 replicates). Nitrogen (N), phosphorous (P), and potassium (K) at rates of 160 kg N ha^{-1}, 35 kg P ha^{-1}, and 35 kg K ha^{-1} were supplied to the experimental plots before sowing, according to the local practice.

The weather data were obtained from the weather station near the experiment site. The mean temperatures were 10.2, 9.5, and 11.0 °C, whereas the precipitation was 377, 316, and 367 mm for the 2017–2018, 2018–2019, and 2019–2020 growing seasons, respectively (Supplementary Materials Figure S1).

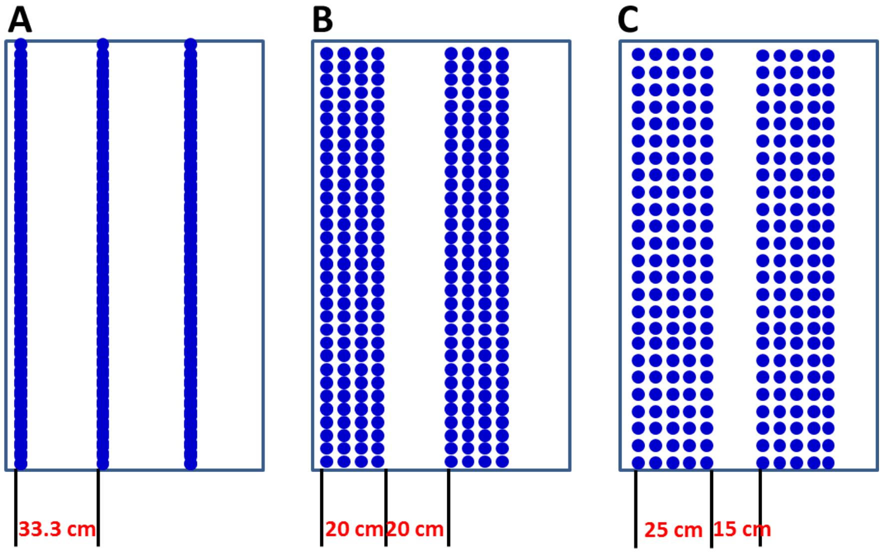

Figure 1. The three sowing patterns ((**A**): line and dense sowing with 33.3 cm row space (LDS). (**B**): belt uniform sowing with 20 cm row space (BUN). (**C**): belt uniform sowing with narrow (15 cm) row space (BUW)) used in this study. All sowing patterns have the same seed rate.

2.1. Sampling and Measurements

At final harvest, when each cultivar reached maturity, two center rows on each plot were harvested by cutting each plant at about 1 cm above soil surface. The sample for each plot was sealed in a nylon bag, which was tagged with the plot information. Then all the bags were transported to the lab after harvest for processing.

The spike number was counted and recorded for each sample, and then we cut the spike from the shoot and placed it in the envelope with plot information. The leaf and stem were separated and placed in the envelopes separately. All the samples were dried in the oven at 80 °C for 48 h, and then weighed to get the dry weight for different parts. After drying, 20 representative spikes for each plot were used to measure the grain weight and grain number per spike. The other spikes were threshed by hand to get the grains, then weighted and combined with the grain weight of the 20 representative spikes to get the grain yield for each plot. The shoot dry weight was obtained by adding the dry weight of the spike, stem, and leaf. The harvest index (HI) =grain yield/shoot dry weight. The grain yield (g m^{-2}) = grain yield for each plot/harvest area. The spike, leaf, and stem dry weight (g m^{-2}) was calculated by dividing the dry weight by harvest area.

2.2. Statistics Analysis

The effects of the sowing density and sowing pattern, and their interaction on grain yield, shoot dry weight, HI, and yield components were analyzed by a two-way analysis of variance (ANOVA) by using Gen-Stat 19.0 (VSN International Ltd., Rothamsted, UK). All figures were drawn with Origin 2020 (Origin Lab, Northampton, MA, USA). The figures were shown as box plot, using the combined data for four cultivars. The linear model was used to fit the curve between the grain yield and shoot dry weight, between the spike number and shoot dry weight. The linear model was used to fit the curve among the spike, leaf, and stem dry weight, and the slopes were used to compare the allometric growth among the spike, leaf, and stem by multiple comparison (Duncan test). The Spearman correlation was used to generate the correlation matrix among the grain yield, yield components, shoot dry weight, and HI.

3. Results

3.1. Yield and Yield Components

The results show that the belt uniform sowing (BU) could significantly increase the grain yield in all four winter wheat cultivars in each sowing density in three consecutive growing seasons (Figure 2A–C). The yield improvements with BU in the high sowing density (300 and 375 plants m^{-2}) were significantly higher than in lower sowing density (75 and 150 plants m^{-2}). The high grain yield with BU was associated with the higher shoot dry weight in the three years (Figure 2D–F). Compared to the grain yield and shoot dry weight, the harvest index (HI) was stable under different sowing densities and sowing patterns (Figure 2G–I).

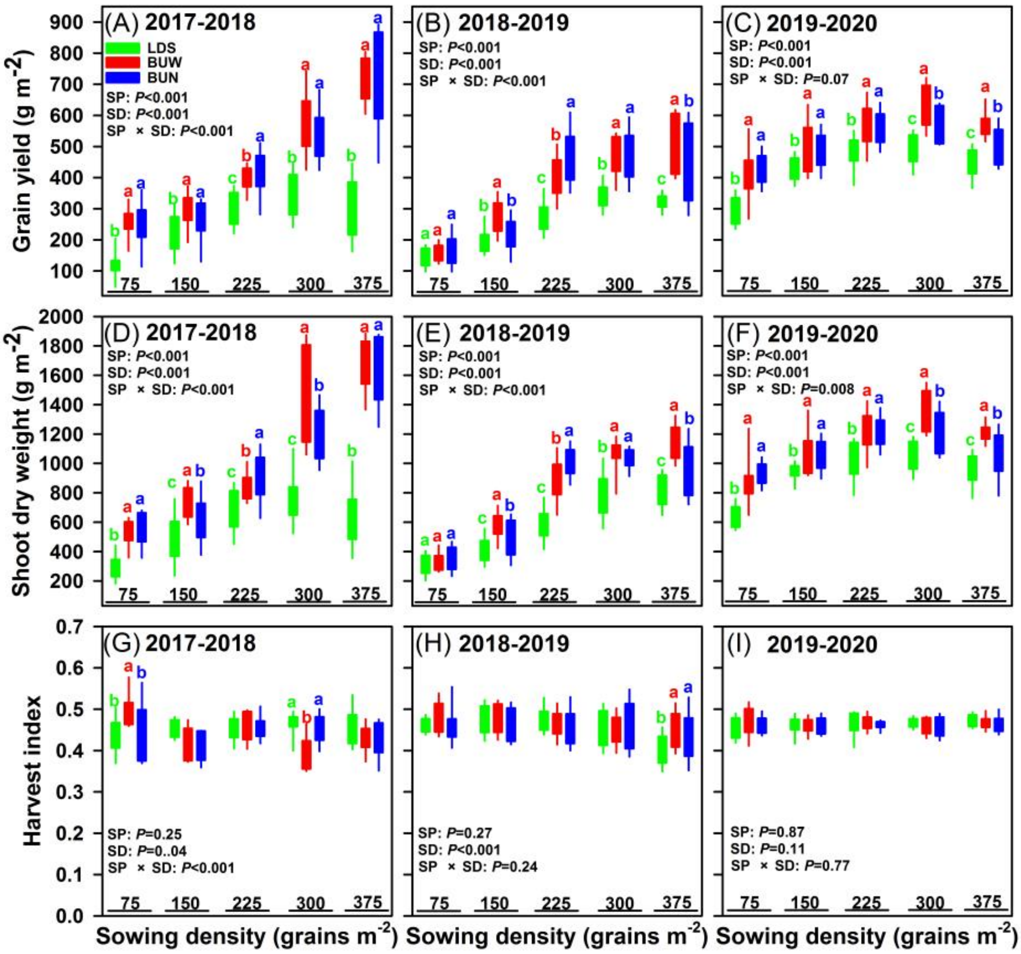

Figure 2. The changes of the (**A**–**C**) grain yield (g m^{-2}), (**D**–**F**) shoot dry weight (g m^{-2}), and (**G**–**I**) harvest index under three sowing patterns (SP; line and dense sowing with 33.3 cm row spacing (LDS); belt uniform sowing with 20 cm row spacing (BUW); and belt uniform sowing with 15 cm row spacing (BUN)) and five sowing densities (SD; 75, 150, 225, 300, and 375 plants m^{-2}) in the three consecutive growing seasons. The different letters mean significant difference between the sowing patters at the same sowing density.

The spike number was significantly increased with the sowing density, and the spike number with belt uniform sowing patterns was significantly higher than the line and dense sowing (LDS) patterns (Figure 3A–C); the interaction between the sowing density and sowing patterns on the spike number was significant. The other yield components (thousand-grain weight and grain number per spike) were stable under different sowing patterns, but the grain number per spike was decreased with the increase in the sowing density (Figure 3D–I); additionally, the grain weight per spike was also decreased when the sowing density increased (Figure 3J–L). The grain yield and spike number gap between the belt uniform and line and dense sowing pattern were significantly positive with the shoot dry weight gap between the belt uniform and line and dense sowing pattern (Figure 4).

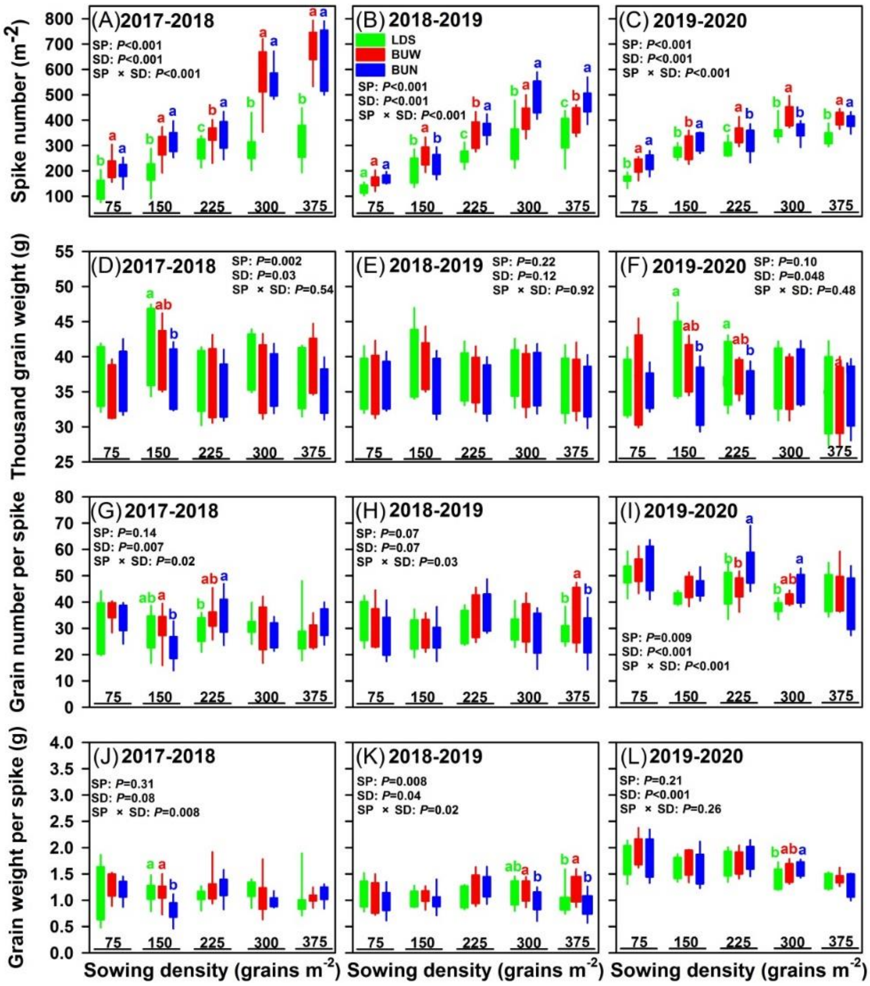

Figure 3. The changes of the (**A**–**C**) spike number (g m^{-2}), (**D**–**F**) thousand-grain weight (g m^{-2}), (**G**–**I**) seed number per spike, and (**J**–**L**) grain weight per spike under three sowing patterns (SP; line and dense sowing with 33.3 cm row spacing (LDS); belt uniform sowing with 20 cm row spacing (BUW); and belt uniform sowing with 15 cm row spacing (BUN)) and five sowing density (SD; 75, 150, 225, 300, and 375 plants m^{-2}) in the three consecutive growing seasons. The different letters mean significant difference between the sowing patters at the same sowing density.

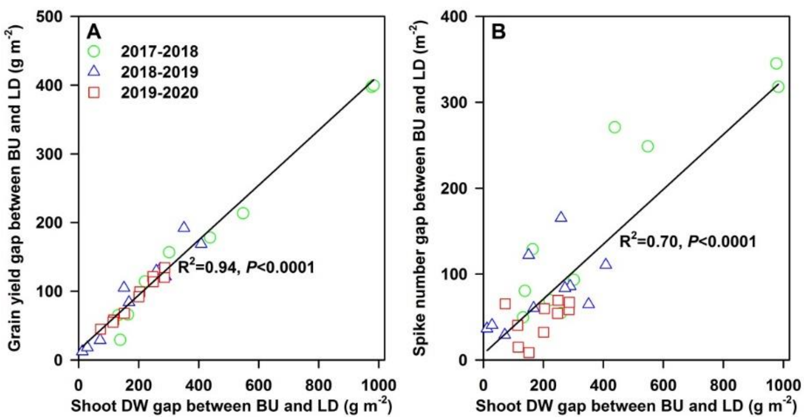

Figure 4. The relationship between the (**A**) grain yield (g m^{-2}) gap and shoot dry weight (DW) gap (g m^{-2}), (**B**) spike number (m^{-2}) gap and shoot dry weight (DW) gap (g m^{-2}), between the belt uniform (BU) and line and dense (LD) sowing patterns and five sowing density (SD; 75, 150, 225, 300, and 375 plants m^{-2}) in the three consecutive growing seasons.

3.2. Allometric and Correlated Analysis

The leaf, stem, and spike dry weight were significantly increased with the increase in the sowing density (Figures 5, 6 and S2). The slopes between the spike and stem dry matter under belt uniform sowing patterns were significantly higher than the line and dense sowing patterns in three ((B) Guizi 4, (C) Guinong 19, and (D) Guinong 30) of the four wheat cultivars (Figure 5), while the slopes between the spike and leaf dry matter under belt uniform sowing patterns were significantly higher than the line and dense sowing patterns of all four wheat cultivars (Figure 6). The slopes can be used to show the relative growth between different organs, thus the high slopes clearly indicated more biomass was partitioned to the spike than the stem and leaf in belt uniform sowing patterns than under line and dense sowing patterns. The ratio between the stem and leaf dry weight was varied among the four wheat cultivars (Figure S2).

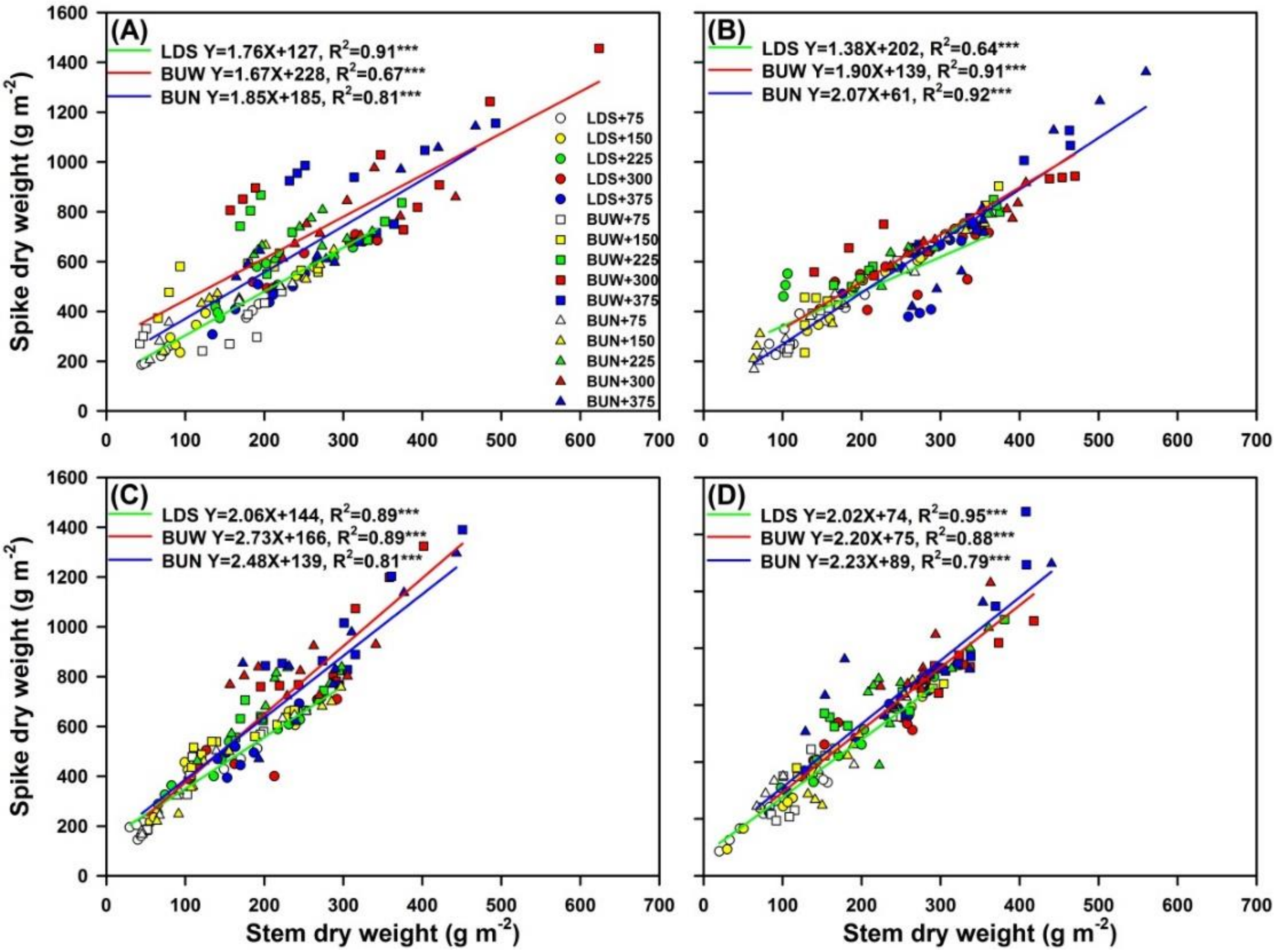

Figure 5. The ratio of spike dry matter to stem dry matter for (**A**) Guizi 1, (**B**) Guizi 4, (**C**) Guinong 19, and (**D**) Guinong 30 under three sowing patterns (SP; line and dense sowing with 33.3 cm row spacing (LDS); belt uniform sowing with 20 cm row spacing (BUW); and belt uniform sowing with 15 cm row spacing (BUN)) and five sowing density (SD; 75, 150, 225, 300, and 375 plants m^{-2}) in the three consecutive growing seasons. *** $p < 0.001$.

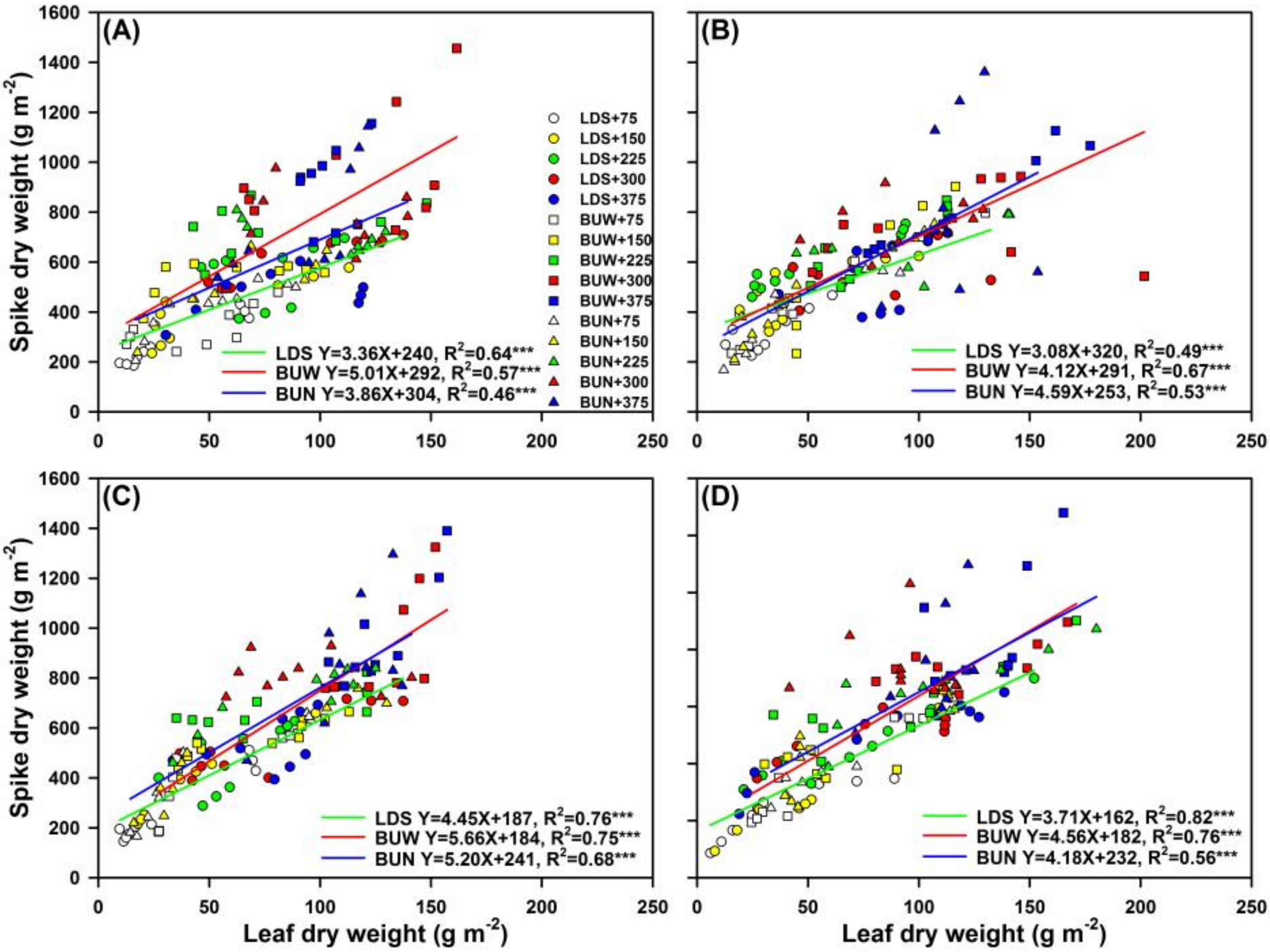

Figure 6. The ratio between the spike dry matter to leaf dry matter (**A**) Guizi 1, (**B**) Guizi 4, (**C**) Guinong 19, and (**D**) Guinong 30 under three sowing patterns (SP; line and dense sowing with 33.3 cm row spacing (LDS); belt uniform sowing with 20 cm row spacing (BUW); and belt uniform sowing with 15 cm row spacing (BUN)) and five sowing density (SD; 75, 150, 225, 300, and 375 plants m^{-2}) in the three consecutive growing seasons. *** $p < 0.001$.

The correlation analysis showed the grain yield was significantly correlated in relation to the shoot dry weight, spike number per m^2, grain number per spike, and grain weight per spike, and the highest correlation was observed between the grain yield and shoot dry weight (Figure 7); while the shoot dry matter can explain the 94% change in the grain yield. The shoot dry weight was significantly positive with the spike number per m^2, grain number per spike, and grain weight per spike; while the highest correlation was observed between the shoot dry weight and spike number per m^2, indicating that most of the g variation (66%) in the spike number can be explained by the variation in the shoot dry weight. The negative relation between the thousand-grain weight and grain number per spike, spike number per m^2, and grain number per spike, as well as spike number per m^2 and grain weight per spike were observed (Figure 7).

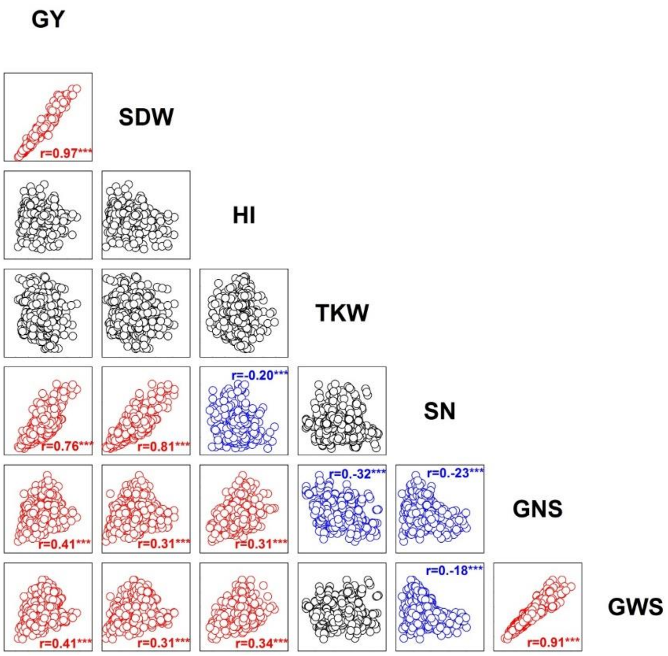

Figure 7. The correlation matrix between the grain yield (GY), shoot dry weight (SDW), harvest index (HI), thousand grain weight (TKW), spike number per m^{-2} (SN), grain number per spike (GNS), and grain weight per spike (GWS). *** $p < 0.001$.

4. Discussion

4.1. Yield Components and Grain Yield

In our previous study, we found that the belt uniform sowing could improve the grain yield of four different wheat cultivars [8]. In this study, we further found that the belt uniform sowing could increase the winter wheat grain yield in five different sowing densities that varied from 75 to 375 grains per m^2. Especially in the higher sowing density (300 and 375 grain per m^2), the grain yield gap between the belt uniform sowing and line and dense sowing was larger than that under lower sowing densities (75 and 150 grains per m^2). Thus the belt uniform sowing patterns could achieve higher grain yield than line and dense sowing patterns, especially under the high sowing density (300 and 375 grain per m^2). The variation in yield components is associated with the improvement of the grain yield [32–35]. Wang et al. [11] observed the spike number per m^2 significantly increased while the grain number per spike and grain size significantly reduced with the increasing of the sowing density, and this was also observed in other studies [36,37]. In our study, the spike number per m^2 was significantly increased while the other two yield components were not significantly changed with the sow densities increasing under belt uniform sowing patterns (Figure 3). Additionally, a significant interaction between the sowing density and sowing pattern on spike number per m^2 was observed for three consecutive years, indicating the belt uniform sowing could not only produce more spike number but also can maintain the grain size and grain number per spike to achieve the high grain yield potential. The high sowing density can lead to grain yield loss because the competition among the plant individuals was increased with sowing density [29]. However, we found the belt uniform sowing patterns could achieve higher grain yield under high sowing density than line and dense sowing patterns, which was associated with the reducing of competition among individuals at higher sowing density, and this may be the other reason why the belt uniform sowing can obtain high grain yield.

4.2. Dry Matter Accumulation and Partition and Yield Formation

The dry matter accumulation played an important role in yield formation because the high dry matter accumulation may provide more carbohydrates to format the flower and grain, improve grain filling, and increase grain size [33], which was the determined factor related to the grain yield in wheat. In this study, a significant increasing in the shoot dry matter was observed in belt uniform sowing in five sowing densities. The variation in the shoot dry matter can explain 94% of the increasing in the grain yield and 66% of the improvement of the spike number per m^2 (Figure 3). A significant interaction between the sowing density and sowing pattern on shoot dry weight was observed in three consecutive years, indicating that the belt uniform sowing could produce more shoot dry weight, especially under high sowing density. Increasing the leaf area index to improve the interception of the solar could be one reason to achieve high shoot dry weight [38,39] in belt uniform sowing. Furthermore, the optimal canopy architecture can increase the photosynthesis rate to benefit dry matter accumulation [10,31]. The high shoot dry matter accumulation may help to explain why both the grain size and grain number per spike were maintained in a belt uniform sowing pattern.

The dry matter partition also showed an important role in yield performance. Previous studies showed new cultivars could allocate more dry weight to the seed to achieve high yield potential in crops [33,40,41]. The genetic improvement of the grain yield was tightly linked to the increase in the harvest index in wheat and other crops [2,23,35,40]. In our study, we found that the harvest index was not significantly changed under different sowing densities and patterns, indicating that the yield improvements were dependent on the dry matter accumulation rather than the harvest index. However, the allometric analysis shows the relative growth of the spike was higher than the leaf and the stem (Figures 4 and 5), especially under high sowing density, and this result clearly shows that more dry matter was partitioned to the spike than the stem and leaf. Thus, the increasing of the shoot dry weight was coordinated with the high dry matter partition to the spike to achieve the high yield potential at high sowing density with the belt uniform sowing pattern.

5. Conclusions

In this study, the BU pattern achieved significantly higher grain yield than line and dense sowing patterns, and this was associated with the improvement of the shoot dry weight and the spike number per m^2. The relative growth of the spike to stem and leaf was higher in the belt uniform sowing than the line and dense sowing, which was the other reason for high yield potential in BU patterns.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12122936/s1, Figure S1: The precipitation and mean temperature changes in the field experiment during the growing season for (A) 2017–2018, (B) 2018–2019 and (C) 2019–2020; Figure S2. The ratio of the stem dry matter to leaf dry matter (A) Guizi 1, (B) Guizi 4, (C) Guinong 19 and (D) Guinong 30 under three sowing patterns (SP; Line and dense sowing with 33.3 cm row spacing (LDS); Belt uniform sowing with 20 cm row spacing (BUW); and Belt uniform sowing with 15 cm row spacing (BUN)) and five sowing density (SD; 75, 150, 225, 300 and 375 plants m^{-2}) in the three consecutive growing seasons.

Author Contributions: Conceptualization, J.H. and R.D.; methodology, M.C.; formal analysis, M.C. and Y.-H.Z.; investigation, M.C., Y.-H.Z. and J.H.; writing—original draft preparation, M.C., L.J., M.-J.R. and J.H.; writing—review and editing, M.C., L.J., Y.-H.Z., J.H. and R.D.; supervision, J.H. and R.D.; funding acquisition, J.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Guizhou Science and Technology Support Program Project (Qiankehezhicheng (2021) yiban217; Qiankehechengguo (2019)4246), the National Natural Science Foundation of China (32260481).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Porkka, M.; Kummu, M.; Siebert, S.; Varis, O. From food insufficiency towards trade dependency: A historical analysis of global food availability. *PLoS ONE* **2013**, *8*, e82714. [CrossRef] [PubMed]
2. Liu, L.; Sadras, V.O.; Xu, J.A.; Hu, C.L.; Yang, X.Y.; Zhang, S.L. Genetic improvement of crop yield, grain protein and nitrogen use efficiency of wheat, rice and maize in china. *Adv. Agron.* **2021**, *168*, 203–252.
3. Asseng, S.; Martre, P.; Maiorano, A.; Rötter, R.P.; O'Leary, G.J.; Fitzgerald, G.J.; Girousse, C.; Motzo, R.; Giunta, F.; Babar, M.A.; et al. Climate change impact and adaptation for wheat protein. *Global Change Biol.* **2019**, *25*, 155–173. [CrossRef] [PubMed]
4. Guo, J.; Liu, X.; Zhang, Y.; Shen, J.; Han, W.; Zhang, W.; Christie, P.; Goulding, K.W.T.; Vitousek, P.M.; Zhang, F.S. Significant acidification in major Chinese croplands. *Science* **2010**, *327*, 1008–1010. [CrossRef] [PubMed]
5. Lobell, D.B.; Schlenker, W.; Costa-Roberts, J. Climate trends and global crop production since 1980. *Science* **2011**, *333*, 616–620. [CrossRef]
6. Snowdon, R.J.; Wittkop, B.; Chen, T.W.; Stahl1, A. Crop adaptation to climate change as a consequence of long-term breeding. *Theor. Appl. Genet.* **2021**, *134*, 1613–1623. [CrossRef]
7. Langridge, P.; Reynolds, M. Breeding for drought and heat tolerance in wheat. *Theor. Appl. Genet.* **2021**, *134*, 1753–1769. [CrossRef]
8. Chen, T.; Zhu, Y.H.; Dong, R.; Ren, M.J.; He, J.; Li, F.M. Belt uniform sowing pattern boosts yield of different winter wheat cultivars in southwest China. *Agriculture* **2021**, *11*, 1077. [CrossRef]
9. Jiao, F.; Hong, S.Z.; Liu, C.Y.; Ma, Y.Z.; Zhang, M.M.; Li, Q.Q. Wide-precision planting pattern under different tillage methods affects photosynthesis and yield of winter wheat. *Arch. Agron. Soil Sci.* **2022**, *68*, 1352–1368. [CrossRef]
10. Li, D.X.; Zhang, D.; Wang, H.G.; Li, H.R.; Fang, Q.; Li, H.Y.; Li, Q.Q. Optimized planting density maintains high wheat yield under limiting irrigation in North China Plain. *Int. J. Plant Prod.* **2020**, *14*, 107–117. [CrossRef]
11. Wang, Z.; Khan, S.; Sun, M.; Ren, A.X.; Lin, W.; Ding, P.C.; Noor, H.; Yu, S.B.; Feng, Y.; Wang, Q.; et al. Optimizing the wheat seeding rate for wide-space sowing to improve yield and water and nitrogen utilization. *Int. J. Plant Prod.* **2021**, *15*, 553–562. [CrossRef]
12. Liu, H.; Yu, L.; Luo, Y.; Wang, X.; Huang, G. Responses of winter wheat (*Triticum aestivum* L.) evapotranspiration and yield to sprinkler irrigation regimes. *Agri. Water Manag.* **2011**, *198*, 483–492. [CrossRef]
13. Asim, M.; Khan, M.I.; Rab, A. Productivity and the qualitative response of sorghum to different planting patterns and various cultivars. *J. Soil Plant Environ.* **2022**, *1*, 89–101. [CrossRef]
14. Abdelhadi, A.W.; El, A.; Bashir, M.A.; Hata, T. Evaluation of wheat bed planting system in irrigated vertisols of Sudan. *Agric. Mech. Asia Afr. Lat. Am.* **2006**, *37*, 62–67.
15. Choudhury, B.U.; Bouman, B.; Singh, A.K. Yield and water productivity of rice—Wheat on raised beds at New Delhi, India. *Field Crops Res.* **2007**, *100*, 229–239. [CrossRef]
16. Zhang, J.; Sun, J.; Duan, A.; Wang, J.; Shen, X.; Liu, X. Effects of different planting patterns on water use and yield performance of winter wheat in the Huang-Huai-Hai plain of China. *Agri. Water Manag.* **2007**, *92*, 41–47. [CrossRef]
17. Li, Q.Q.; Zhou, X.B.; Chen, Y.H.; Yu, S.L. Water consumption characteristics of winter wheat grown using different planting patterns and deficit irrigation regime. *Agri. Water Manag.* **2012**, *105*, 8–12.
18. Li, Q.; Bian, C.; Liu, X.; Ma, C.; Liu, Q. Winter wheat grain yield and water use efficiency in wide-precision planting pattern under deficit irrigation in North China Plain. *Agri. Water Manag.* **2015**, *153*, 71–76. [CrossRef]
19. Bian, C.Y.; Ma, C.J.; Liu, X.H.; Gao, C.; Liu, Q.R.; Yan, Z.X.; Ren, Y.J.; Li, Q.Q. Responses of winter wheat yield and water use efficiency to irrigation frequency and planting pattern. *PLoS ONE* **2016**, *11*, e0154673. [CrossRef]
20. Liu, C.; Jia, Y.; Zhang, J.; Sun, P.; Li, J.; Li, P.; Shi, S. Effects of sowing patterns and irrigation amount on dry matter and yield of spring wheat. *J. Triticeae Crops* **2019**, *39*, 728–737.
21. Ali, S.; Xu, Y.; Ma, X.; Jia, Q.; Jia, Z. Farming practices and deficit irrigation management improve winter wheat crop water productivity and biomass through mitigated greenhouse gas intensity under semi-arid regions. *Environ. Sci. Pollut. Res.* **2021**, *28*, 27666–27680. [CrossRef] [PubMed]
22. Qin, X.L.; Weiner, J.; Qi, L.; Xiong, Y.C.; Li, F.M. Allometric analysis of the effects of density on reproductive allocation and Harvest Index in 6 varieties of wheat (*Triticum aestivum* L.). *Field Crops Res.* **2013**, *144*, 162–166. [CrossRef]
23. He, J.; Du, Y.L.; Wang, T.; Turner, N.C.; Xi, Y.; Li, F.M. Old and new cultivars of soya bean (*Glycine max* L.) subjected to soil drying differ in abscisic acid accumulation, water relations characteristics and yield. *J. Agron Crop. Sci* **2016**, *202*, 372–383. [CrossRef]
24. Fang, Y.; Xu, B.C.; Turner, N.C.; Li, F.M. Grain yield, dry matter accumulation and remobilization, and root respiration in winter wheat as affected by seeding rate and root pruning. *Eur. J. Agron.* **2010**, *33*, 257–266. [CrossRef]
25. Dai, X.L.; Zhou, X.H.; Jia, D.Y.; Xiao, L.L.; Kong, H.B.; He, M.G. Managing the seeding rate to improve nitrogen–use efficiency of winter wheat. *Field Crops Res.* **2013**, *154*, 100–109. [CrossRef]
26. Chauhdary, J.N.; Khan, U.D.; Shah, S.H.H.; Shahid, M.A.; Arsalan, M. Effect of sowing methods and seed rates on wheat yield and water productivity. *Qual. Assur. Saf. Crops* **2016**, *8*, 267–272. [CrossRef]
27. Tao, Z.Q.; Ma, S.K.; Chang, X.H.; Wang, D.; Wang, Y.J.; Yang, Y.S.; Zhao, G.C.; Yang, J.C. Effects of tridimensional uniform sowing on water consumption, nitrogen use, and yield in winter wheat. *Crop J.* **2019**, *7*, 480–493. [CrossRef]
28. Kiss, T.; Balla, K.; Banyai, J.; Veisz, O.; Karsai, I. Associations between plant density and yield components using different sowing times in wheat (*Triticum aestivum* L.). *Cereal Res. Commun.* **2018**, *46*, 211–220. [CrossRef]

29. Hiltbrunner, J.; Streit, B.; Liedgens, M. Are seeding densities an opportunity to increase grain yield of winter wheat in a living mulch of white clover? *Field Crops Res.* **2007**, *102*, 163–171. [CrossRef]
30. Roques, S.E.; Berry, P.M. The yield response of oilseed rape to plant population density. *J. Agr. Sci.* **2016**, *154*, 305–320. [CrossRef]
31. Zhang, D.S.; Zhang, L.Z.; Liu, J.G.; Han, S.; Wang, Q.; Evers, J.; Liu, J.; van der Werf, W.; Li, L. Plant density affects light interception and yield in cotton grown as companion crop in young jujube plantations. *Field Crops Res.* **2014**, *169*, 132–139. [CrossRef]
32. He, J.; Jin, Y.; Du, Y.L.; Wang, T.; Turner, N.C.; Yang, R.P.; Siddique, K.H.M.; Li, F.M. Genotypic variation in yield, yield components, root morphology and architecture, in soybean in relation to water and phosphorus supply. *Front. Plant. Sci.* **2017**, *8*, 1499. [CrossRef]
33. He, J.; Jin, Y.; Turner, N.C.; Chen, Z.; Liu, H.Y.; Wang, X.L.; Siddique, K.H.M.; Li, F.M. Phosphorus application increases root growth, improves daily water use during the reproductive stage, and increases grain yield in soybean subjected to water shortage. *Environ. Exp. Bot* **2019**, *166*, 103816. [CrossRef]
34. Zhang, Z.H.; Palta, J.A.; Lu, P.; Ren, M.J.; Zhu, X.T.; He, J. Traditional soybean (*Glycine max*) breeding increases seed yield but reduces yield stability under non-phosphorus supply. *Funct. Plant Biol.* **2022**, *49*, 132–144. [CrossRef]
35. Yang, J.X.; Richards, R.A.; Jin, Y.; He, J. Both biomass accumulation and harvest index drive the yield improvements in soybean at high and low phosphorus in south-west China. *Field Crops Res.* **2022**, *277*, 108426. [CrossRef]
36. Borrás, L.; Maddonni, G.A.; Otegui, M.E. Leaf senescence in maize hybrids: Plant population: Row spacing and kernel set effects. *Field Crops Res.* **2003**, *82*, 13–26. [CrossRef]
37. Echarte, L.; Luque, S.; Andrade, F.H.; Sadras, V.O.; Cirilo, A.; Otegui, M.E.; Vega, C.R.C. Response of maize kernel number to plant density in Argentinean hybrids released between 1965 and 1993. *Field Crops Res.* **2000**, *68*, 1–8. [CrossRef]
38. Jia, Q.M.; Sun, L.F.; Mou, H.Y.; Ali, S.; Liu, D.H.; Zhang, Y.; Zhang, P.; Ren, X.L.; Jia, Z.K. Effects of planting patterns and sowing densities on grain-filling, radiation use efficiency and yield of maize (*Zea mays* L.) in semi-arid regions. *Agri. Water Manag.* **2018**, *201*, 287–298. [CrossRef]
39. Du, X.B.; Wang, Z.; Xi, M.; Wu, W.G.; Wei, Z.; Xu, Y.Z.; Zhou, Y.J.; Lei, W.X.; Kong, L.C. A novel planting pattern increases the grain yield of wheat after rice cultivation by improving radiation resource utilization. *Agr. Forest Meteorol.* **2021**, *310*, 108625. [CrossRef]
40. Wang, T.; Du, Y.L.; He, J.; Turner, N.C.; Wang, B.R.; Zhang, C.; Cui, T.; Li, F.M. Recently-released genotypes of naked oat (*Avena nuda* L.) out-yield early releases under water-limited conditions by greater reproductive allocation and desiccation tolerance. *Field Crops Res.* **2017**, *204*, 169–179. [CrossRef]
41. Jin, Y.; He, J.; Turner, N.C.; Du, Y.L.; Li, F.M. Water-conserving and biomass-allocation traits are associated with higher yields in modern cultivars compared to landraces of soybean [*Glycine max* (L.) Merr.] in rainfed water-limited environments. *Environ. Exp. Bot* **2019**, *168*, 103883. [CrossRef]