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Revolutionizing Maize Crop Productivity: The Winning Combination of Zigzag Planting and Deep Nitrogen Fertilization for Maximum Yield through Root–Shoot Ratio Management

Yongzhao Zheng [1,2], Yang Yue [1,2], Congfeng Li [3], Yongjun Wang [4], Hongyu Zhang [5], Hong Ren [1], Xiangwei Gong [1], Ying Jiang [1,*] and Hua Qi [1,*]

[1] College of Agronomy, Shenyang Agricultural University, Shenyang 110866, China; zyz7068@163.com (Y.Z.); yueyang7069@163.com (Y.Y.); 2018200044@stu.syau.edu.cn (H.R.); gongxiangwei@syau.edu.cn (X.G.)
[2] Tonghua Academy of Agricultural Sciences, Meihekou 135000, China
[3] Institute of Crop Science, Chinese Academy of Agricultural Sciences, Beijing 100081, China; licongfeng@caas.cn
[4] State Engineering Laboratory of Maize, Institute of Agricultural Resources and Environment, Jilin Academy of Agriculture Sciences, Changchun 130033, China; yjwang2008@cjaas.com
[5] Farming and Animal Husbandry Bureau of Tongliao, Tongliao 028005, China; zhanghongyu2006@126.com
* Correspondence: jiangying@syau.edu.cn (Y.J.); qihua10@syau.edu.cn (H.Q.)

Abstract: Maize is the staple food of China, produced on 33.6% of the total arable land. In this context, an effective strategy to enhance maize yield is essential to meet the demand without expanding the cultivation areas. Maize yield can be increased by two key measures: plant-row space optimization and nutrient management. However, in traditional maize cultivation practices, fertilizer utilization by plants is inefficient. We therefore performed a manipulative experiment over two years (2018–2019), applying four treatments: (I) linear planting with nitrogen fertilization at 10 cm depth (CK), (II) linear planting with nitrogen fertilization at 20 cm depth (LD20), (III) zigzag planting with nitrogen fertilization at 10 cm depth (ZD10), and (IV) zigzag planting with nitrogen fertilization at 20 cm depth (ZD20). The aim of this study was to examine the influence of deep nitrogen fertilization and zigzag planting alone and in combination with root distribution, soil properties, canopy structures, and maize yield. Our results showed that all improved maize cultivating strategies (LD20, ZD10, and ZD20) increased the root length density up to 10–30 cm depth of soil layers compared to CK. Similarly, deep nitrogen fertilization increased the photosynthesis rate and leaf area duration after the silking stage. The leaf orientation value of the middle and upper canopies increased in zigzag planting compared to linear planting. It also increased the dry matter accumulation of medium leaves, leaf area duration, and dry matter accumulation after the silking stage. The maize yield was highly increased in ZD20 followed by ZD10, LD20, and the least by CK (traditional cultivating practices) in both years. Our study suggests that zigzag planting provides a higher yield than linear planting. Additionally, deep nitrogen fertilization in zigzag planting significantly increases the population resource utilization rate and yield by optimizing the root–canopy structures. Row spacing and nitrogen fertilization were found to be essential to enhance crop yield by influencing root growth and canopy efficiency.

Keywords: canopy structure; grain yield; nutrients; plant and row spacing; root morphology; leaf morphology; spring maize (*Zea mays* L.)

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1. Introduction

Maize is one of the main staple foods in China [1]. China demands a total of 282 million tons of maize per year [2]. The total production of maize in China was 257 million tons in 2019, with an increase to 261 million tons and 272 million tons in 2020 and 2021, respectively [3]. This data suggests a huge increment in maize production in 2021, which is due to land expansion [4] and the introduction of new improvised maize varieties. However, it still does not meet the demand of the 10 million tons of maize per year—a demand that is increasing annually. Currently, to cover this demand China imports millions of tons of maize every year [5]. China possesses only 13%, which is 127.86 million hectares of arable land, and out of that 33.63% is used exclusively for maize production [6].

Considering limited arable land [7] and increasing the demand for maize, it is essential to improve traditional planting strategies to substantially enhance maize yield [8]. The current practices of growing spring maize involve linear planting with a space of 60 cm between rows and fertilizer application at a depth of 10 cm for each plant [9,10]. Previous studies on maize plants have reported that optimizing plant-row spacing and improving nutrient management are critical measures for enhancing the yield [11,12]. Optimizing plant-row spacing can be done in two ways: I. wide–narrow row planting patterns and II. expanding plant spacing and shrinking the row spacing [13]. A wide–narrow rows planting pattern improves the utilization of limited resources by enhancing the ventilation and light transmission [14]. However, previous studies [15,16] have suggested that wide–narrow row planting might cause vigorous growth of the maize in the earlier growth stage, resulting in senescence at the later growth stage. In addition, uneven row spacing can lead to poor light interception [8,17]. Alternatively, expanding the plant spacing and shrinking the row spacing [18–20] can increase the yield by more than 10% under the same density of maize plants [21]. However, in cropland, shrinking the row spacing can be harmful as it enhances the intraspecific resource competition between rows [22,23]. To utilize the advantage of wide/narrow row planting and avoid intra-specific competition, some studies [24,25] have suggested zigzag planting as a suitable alternative.

In addition to space optimization by zigzag planting, the availability of required nutrients plays a vital role in enhancing maize yield. Among fertilizers, nitrogen (N) is the most critical nutrient for improving growth throughout the stages of grain production [26]. In current practices, N is supplied at the soil surface and shallow layer (at 10 cm depth). However, surface-shallow N application results in N loss (NH_3 and N_2O) [12,27] or exacerbates area-source pollution [28]. To ensure an effective N supplement without loss, several previous studies [29–31] have reported that N fertilization should be supplied at deep soil layers. Deep N fertilization effectively reduces N loss, promotes root growth, enhances the activity of root enzymes [32], and maintains high NH_4^+-N concentration in deep soil solution [33]. In the study by Wu et al. [34], nitrogen fertilization at 15 cm depth increased the nitrogen uptake by plants and the nitrogen use efficiency by 8.07% and 17.79%, compared to 5 cm depth. A considerable number of studies [12,30,35] over the decades have mainly focused on yield and nitrogen use efficiency under deep nitrogen placement without comparing the structure of the root and canopy. Therefore, the mechanism of yield regulation by root and canopy structure under the deep placement of N fertilizer of spring maize remains unexplored and challenging. Previous studies [24,25,34] on maize yield enhancement have either considered zigzag planting or N fertilization at the deep layers. Zigzag planting alone can reduce plant–plant competition in duplicate rows without changing the row spacing and density [25], whereas N supplement at deep soil layers alone can increase the availability of nutrients [35]. Therefore, combining zigzag planting and deep N fertilization together may significantly enhance the growth and yield of spring maize [18] by reducing fertilizer competition among crops and regulating the root and canopy characteristics of the maize population [13].

In this study, we designed a manipulative experiment to evaluate the effect of zigzag planting and deep nitrogen fertilization on root–canopy characteristics, which eventually enhances the spring maize yield. We used the XiangYu211 variety of spring maize in our study, as this variety is preferred by local maize farmers because of its disease resistance, adaptability to soil and environmental conditions, and its high yield characteristics [36]. We hypothesized that (1) zigzag planting substantially increases maize yield by optimizing the root–canopy structure and enhancing the leaf photosynthetic characteristics; (2) deep N fertilization substantially increases the yield by promoting the growth and absorption of soil nutrients by roots; (3) the combination of zigzag planting and deep N fertilization significantly increases the maize yield by bringing the combined benefits from each of the strategies compared to zigzag planting or deep N fertilization alone. The findings of this study provide a theoretical and practical basis for a new, effective, and efficient method for attaining a high yield of spring maize cultivation without losing the soil quality in Northeast China.

2. Materials and Methods

2.1. Experimental Site and Design

We conducted this study at the Jilin Academy of Agricultural Sciences in Northeast China (43°53′ N, 124°82′ E), where 40% [37] of the total maize in the whole country is produced, therefore playing an irreplaceable role in guaranteeing national food security [38]. Jilin experiences a mid-temperate continental monsoon climate with the lowest temperature reaching −30 °C, leaving only around 144 frost-free days throughout the whole year [39]. Maize is grown locally during those frost-free days, which are between April and October. Therefore, we also followed the same growing period for our study. The mean annual precipitation and ambient temperature at the experimental sites were approximately 560 mm and 17.4 °C, respectively. The active accumulated temperature and precipitation were 3239.7 °C and 538.3 mm in 2018 and 3224.7 °C, and 592.9 mm in 2019 (Figure S1) during our experiment period. The preceding crop was maize.

This study employed a two-factor (i.e., planting manner and N fertilization depth) randomized block design and applied four treatments: (1) linear planting with nitrogen fertilization at 10 cm soil depth (CK, Figure 1a); (2) linear planting with nitrogen fertilization at 20 cm soil depth (LD20, Figure 1b); (3) zigzag planting with nitrogen fertilization at 10 cm soil depth (ZD10, Figure 1c); and (4) zigzag planting with nitrogen fertilization at 20 cm soil depth (ZD20, Figure 1d). There was a total of 12 plots, with each plot measuring 48 m^2 (10 m × 4.8 m). Each plot was divided into 8 rows consisting of 45 maize plants, resulting in a total of 360 individuals each plot. One treatment was applied to one plot and there were three replications for each treatment. Prior to sowing the seed, all plots were supplied with fertilizers: 225 kg N ha^{-1}, 90 kg P_2O_5 ha^{-1}, and 90 kg K_2O ha^{-1}. Phosphorus ($Ca(H_2PO_4)_2$) and potassium (KCL) were applied using a fertilizer machine, whereas nitrogen (Urea) was applied manually at the required depth (depth measured using a ruler) by manual excavation. After fertilization, the soil was backfilled to the ditch. We used the spring maize cultivar XiangYu211, which is widely grown in the study area, and planted a total of 75,000 maize plants ha^{-1}. During the growing season, all maize plants were protected with herbicides and pesticides to avoid weeds and infestations. The maize seeds were sown on 28 April and 26 April and harvested on 28 September in 2018 and 2019, respectively. We adopted different vegetative (VE-VT) and reproductive stages (R1–R6) of the maize life cycle following Ritchie et al. [40].

2.2. Root Spatial Distribution Measurement

We collected maize root samples to measure the change in spatial distribution of the roots in the soil across four different treatments. Root distribution was measured by root length density, which refers to the total length of roots per unit of soil volume [41]. A total of two plants adjacent in different rows were selected for root sampling. Root samples were collected at the silking stage (R1) as this is the highest root development period [42].

To measure root distribution, a soil block (22.2 cm (plant spacing) × 10 cm × 10 cm in size) with an x-axis (horizontal distribution of roots) length of 120 cm and a y-axis (vertical distribution of roots) length of 40 cm was treated as a sampling unit consisting of 48 blocks across all 4 treatments. The y-axis, measuring 40 cm in length, was divided into 4 layers for analysis: 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm. The root length density in each of these layers was then compared between the different treatments. The x-axis was defined as the direction perpendicular to the planting row, and the y-axis was defined as the direction of the soil depth. For each sampling unit, the center of the sampled soil profile was taken as the position of the maize root, following the methodology described in Ref. [43]. The roots from each sampling unit were dug out and washed manually. The washed roots were then scanned using an Epson V700 scanner (Seiko Epson Corp, Nagano, Japan). WinRHIZO software program (Regent Instruments incorporation, Quebec, QC, Canada) was then used to process the scanned images to measure the root length density, and soil volume was added manually.

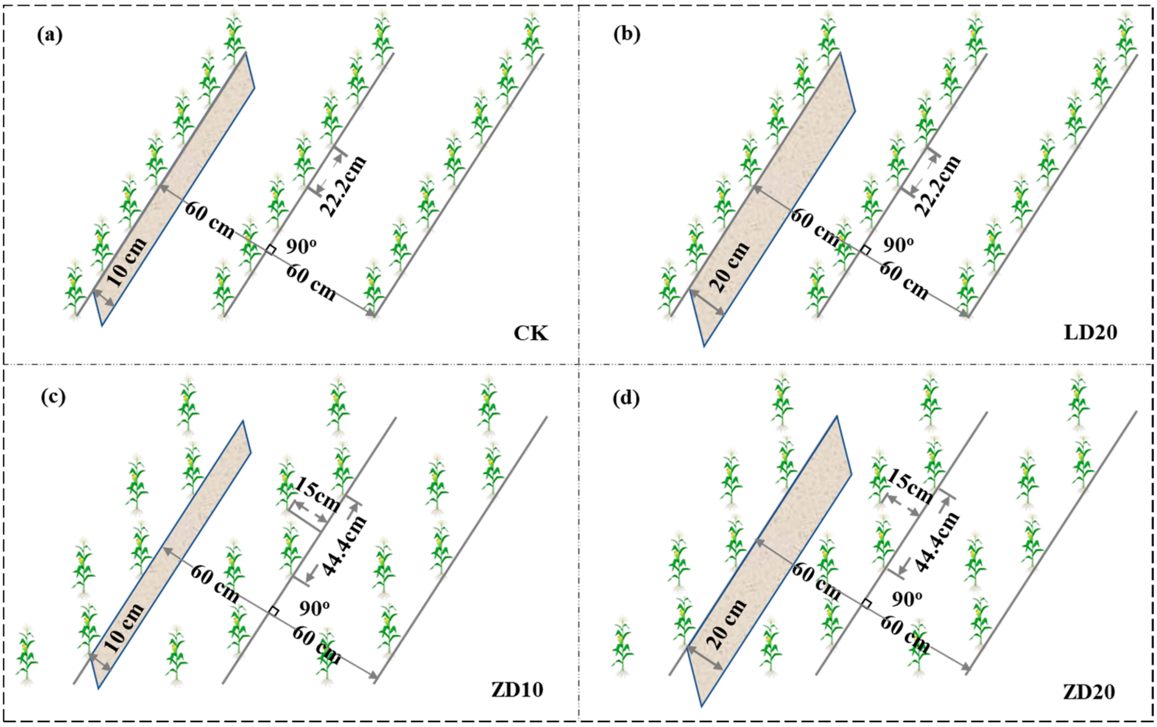

Figure 1. Experimental design of this study. (**a**) CK = linear planting with N fertilization at 10 cm depth, (**b**) LD20 = linear planting with N fertilization at 20 cm depth, (**c**) ZD10 = zigzag planting with N fertilization at 10 cm depth, and (**d**) ZD20 = zigzag planting with N fertilization at 20 cm depth.

2.3. Leaf Characteristics Measurement

To understand the growth of maize plants across treatments, we measured four leaf characteristics: leaf area index (LAI), leaf area duration (LAD), net photosynthetic rate (Pn), and leaf orientation value (LOV) with three replications from each plot. LAI, LAD, and Pn reflect the photosynthetic capacity, whereas LOV reflects the growth condition of the leaves. To measure LAI and LAD, the leaf area (LA) was measured at two stages: silking (R1) and at physiological maturity (R6), because in the R1 stage the leaf area is well developed, and the R6 stage represents the production capacity of the plant. The LA values are then used in Formulas (1) and (2) to calculate LAI and LAD, respectively.

$$\mathrm{LAI} = \mathrm{LA}/\mathrm{GA}, \tag{1}$$

$$\mathrm{LAD}\left(\mathrm{m^2 d\ hm^{-2}}\right) = [(\mathrm{L1} + \mathrm{L2})/2] \times (\mathrm{t2} - \mathrm{t1}), \tag{2}$$

where LA is the leaf area per plant (m^2), GA is the ground area per plant (m^2), t1 and t2 are the adjacent growth stages, and L1 and L2 are the leaf areas at the growth stages of t1 and t2 [44].

Furthermore, we measured the net photosynthetic rate (Pn) of the ear leaf between 10:00 to 14:00 on clear days using the LI6400 portable photosynthesis system analyzer (LI-COR, Lincoln, NE, USA). Leaf Pn was measured at R1 and R6 stages (Pn, CO_2 mol m^{-2} s^{-1} a). To measure LOV, the leaves of each plant were divided into three layers: upper, middle (the middle layer consist of a leaf above the ear, a leaf under the ear, and an ear leaf), and bottom to understand the growth at different leaf positions. The bottom leaves that had half/more than half a yellow area were treated as senesced and avoided. LOV was measured at the R1 stage only and calculated using the following formula:

$$LOV = 1/n \sum(90 - \theta) \times (Lf/LL), \quad (3)$$

where Lf is the length from the base of the ligule to the flagging point of the measured leaf (cm), LL is the total length of leaves (cm), θ is the leaf angle, and n is the number of measured leaves [44].

2.4. Plant Biomass and Grain Yield

We measured the change in plant biomass and grain yield across all treatments. Plant biomass was measured at three growth stages: R1, blister (R2), and R6. Plants at R1 and R6 stages were subjected to both above ground (whole plant) and below ground root biomass measurement. The biomass of plants in the R1 and R6 stages was measured from the same individuals used for LAI measurement. We also tried to explore vertical distribution of biomass using plants in the R2 stages. For this purpose, the plants within a 2 m^2 area (10–13 individuals) were cut from the ground to the top at every 30 cm interval and the roots were dug up to a depth of 30 cm. The leaves, stems, ears, and roots of maize plants were separated. Measurements were taken separately for every 30 cm of biomass. Plants from all three stages were initially dried by heating at 105 °C for 30 min and then oven-dried at 80 °C until a constant weight was achieved [45].

To determine the grain yield, we harvested plants in the middle six rows of each plot, thereby avoiding the boundary effect. Fresh grain weight and moisture content (standardized at 14%) were measured after artificial threshing. Kernels per ear and 1000-kernel weights were measured from 20 samples.

2.5. Soil Physiochemical Properties Measurement

To understand the effect of different cultivation practices (i.e., different treatments in our study) on the physical and chemical properties of soil—especially nutrients—we collected soil samples after harvesting the maize in October 2018 and 2019. The soil of the experimental site was black (Typic Hapludoll, USDA Soil Taxonomy) and has a clay loam texture consisting of 36.0% clay (<0.002 mm), 24.5% silt (0.05–0.002 mm), and 39.5% sand (2.0–0.05 mm). We measured the soil properties of the study area as follows: pH, 5.2; total nitrogen (TN), 1.58 g kg^{-1}; total phosphorus (TP), 0.83 g kg^{-1}; total potassium (TK), 20.13 g kg^{-1}; available nitrogen (AN), 127.5 mg kg^{-1}; available phosphorus (AP), 39.50 mg kg^{-1}; and available potassium (AK), 192.32 mg kg^{-1} in 2018 before the experiment.

We collected five soil cores using an "S-shaped" tool from different depths between 0 to 20 cm and mixed them to form a composite sample. We used fresh soil (50 g) to measure soil mineral nitrogen (NO_3^--N and NH_4^+-N) using a discrete analyzer (Smart Chem 200, KPM Analytics, Westborough, MA, USA) instrument, following Tian et al. [46]. Further, we measured total carbon (TC) using an elemental analyzer (EA3000, Carlo Erba Strumentazione, Milan, Italy) whereas available phosphorus (AP) and available potassium (AK) were measured using spectrophotometer detection and flame photometer detection following Refs. [45,46]. We followed the cutting-ring method to measure soil water contents (SWC) [47].

2.6. Statistical Analysis

In this study, three-way analysis of variance (ANOVA) was used to evaluate the effect of treatments on spatial root distribution, soil physicochemical properties, photosynthetic capacity, growth state of leaves, biomass accumulation, and grain yield. Post hoc pairwise comparisons between treatments with respect to plant growth and yield characteristics were conducted using Duncan's multiple range test. Further, Pearson correlation coefficient was used to examine the relationship between yield and soil physiological properties, leaf source characteristics, and biomass accumulation. All the analyses were compared under the 95% confidence interval. Statistical Package for Social Sciences (SPSS Inc., Chicago, IL, USA) [45] was used for ANOVA and Duncan multiple range test whereas Origin 2021(9.8) software (Origin Lab Inc., Northampton, MA, USA) was used for correlation analysis and graph visualization [41].

3. Results

3.1. Root Spatial Distribution

We found a substantial expansion of roots vertically into the deep soil layers, whereas no differences were observed in horizontal root distribution. Our analysis of variance on root length density revealed significant differences vertically ($p < 0.05$). However, we found no significant ($p = 0.462$) differences horizontally from the plant center (Figure 2) across all four treatments during the two years of the experiment period. Pairwise comparison showed that the ZD20 (12.9%) treatment exhibited the highest root length density followed by Z10 (8.7%) and LD20 (7.1%) vertically compared to CK.

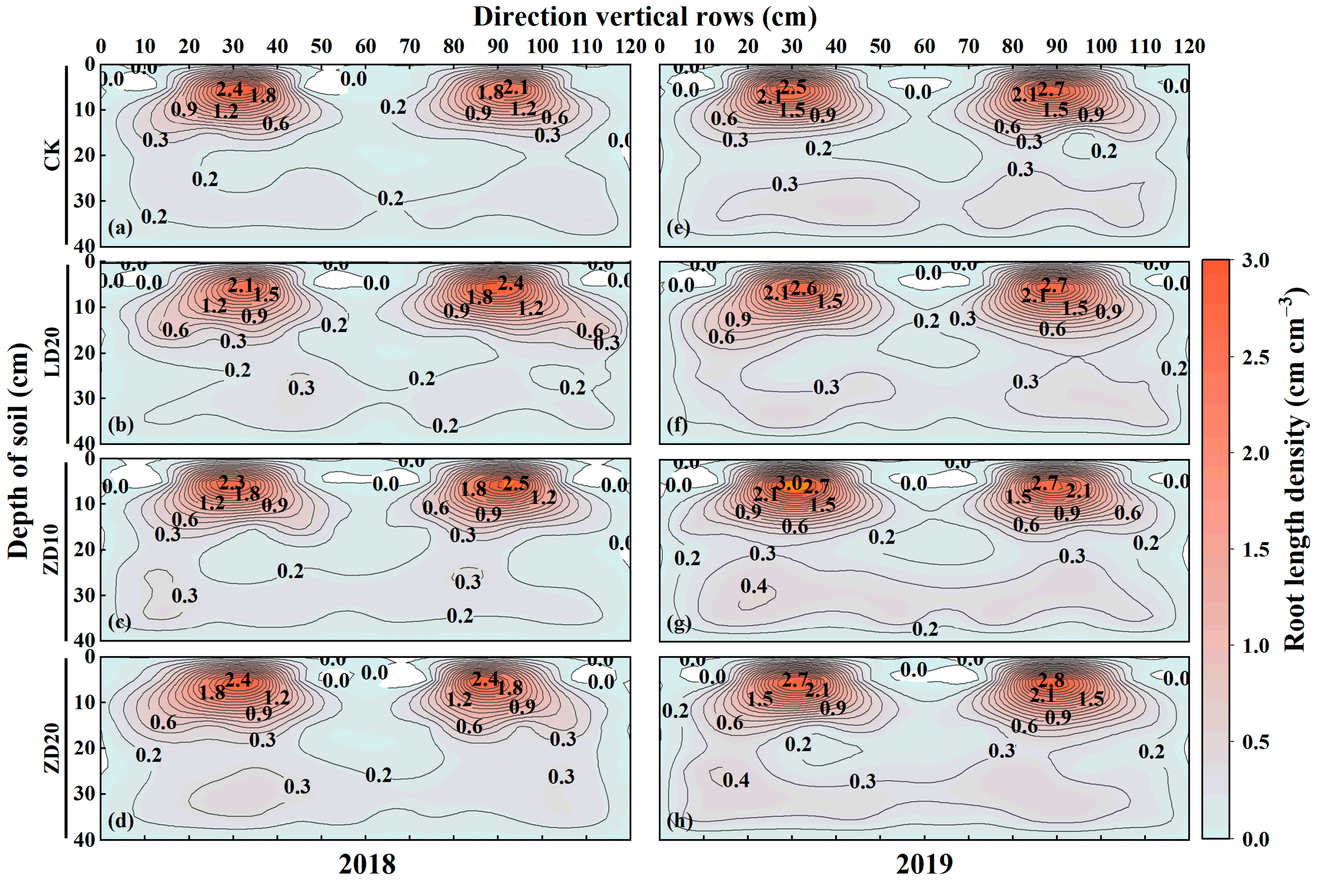

Figure 2. Spatial distribution of root length density in the 0–40 cm soil layer under different cultivation patterns. (**a**,**e**) CK = linear planting with N fertilization at 10 cm depth, (**b**,**f**) LD20 = linear planting with N fertilization at 20 cm depth, (**c**,**g**) ZD10 = zigzag planting with N fertilization at 10 cm depth, and (**d**,**h**) ZD20 = zigzag planting with N fertilization at 20 cm depth.

Furthermore, we compared vertical root length density in each soil layer: 0–10 cm, 10–20 cm, 20–30 cm, and 30–40 cm of CK to the respective layers of treatments: LD20, ZD10, and ZD20. In the 0–10 cm soil layer, there was a significant ($p < 0.05$) difference in root length density only in ZD20 across the treatments. In the 10–20 cm layer, the root length density significantly ($p < 0.05$) increased by 34.5%, 12.7%, and 29.7% across all the treatments, respectively, compared to CK. Similarly, in 20–30 cm, the increment was 5.8%, 13.6%, and

21.4% across the treatments, respectively, compared to CK. Additionally, in the 30–40 cm layer, the root density was increased by 12.7%, and 17.0% across the treatments except for in the LD20 treatment. Moreover, the 20–30 cm and 30–40 cm soil layers under ZD20 treatment were significantly increased by 14.9% and 19.5% compared to LD20 treatment ($p < 0.05$) (Figure 2b,f,d,h). Our result showed that zigzag planting promoted root growth below 10 cm, while deep nitrogen fertilization promoted root growth in the 10–30 cm layers.

3.2. Leaf Morphology and Characteristics

We found substantial differences in photosynthetic capacity and leaf growth across the treatments: LD20, Z10, and Z20 compared to traditional cultivation practices in both years. However, the results of the ANOVA revealed that the year (Y) had a significant ($p < 0.01$) effect on the leaf source characteristics. Similarly, planting manner (P) had a significant ($p < 0.01$) effect on the LAI (R6), Pn (R1), and LAD between R1 and R6 while N depth (D) had a significant ($p < 0.01$) effect on LAI (R6) and Pn (R1 and R6). The interaction of planting manner and N depth (P × D) also had significant ($p < 0.05$) effects on LAI (R6) (Table S1).

This study found that LAI increased significantly ($p < 0.05$) by 14.9% and 16.6% in response to LD20 and ZD10 treatments, respectively, in 2018, whereas an insignificant increasing pattern was observed in 2019 for both treatments. However, a significant ($p < 0.05$) increment in LAI by 22.9% and 16.7% was observed in 2018 and 2019, respectively, under the ZD20 treatments (Figure 3a,d). Increased LAI was observed across treatments LD20, ZD10, and ZD20, respectively, at the R6 stage only, whereas no significant differences were observed at the R1 stage across treatments.

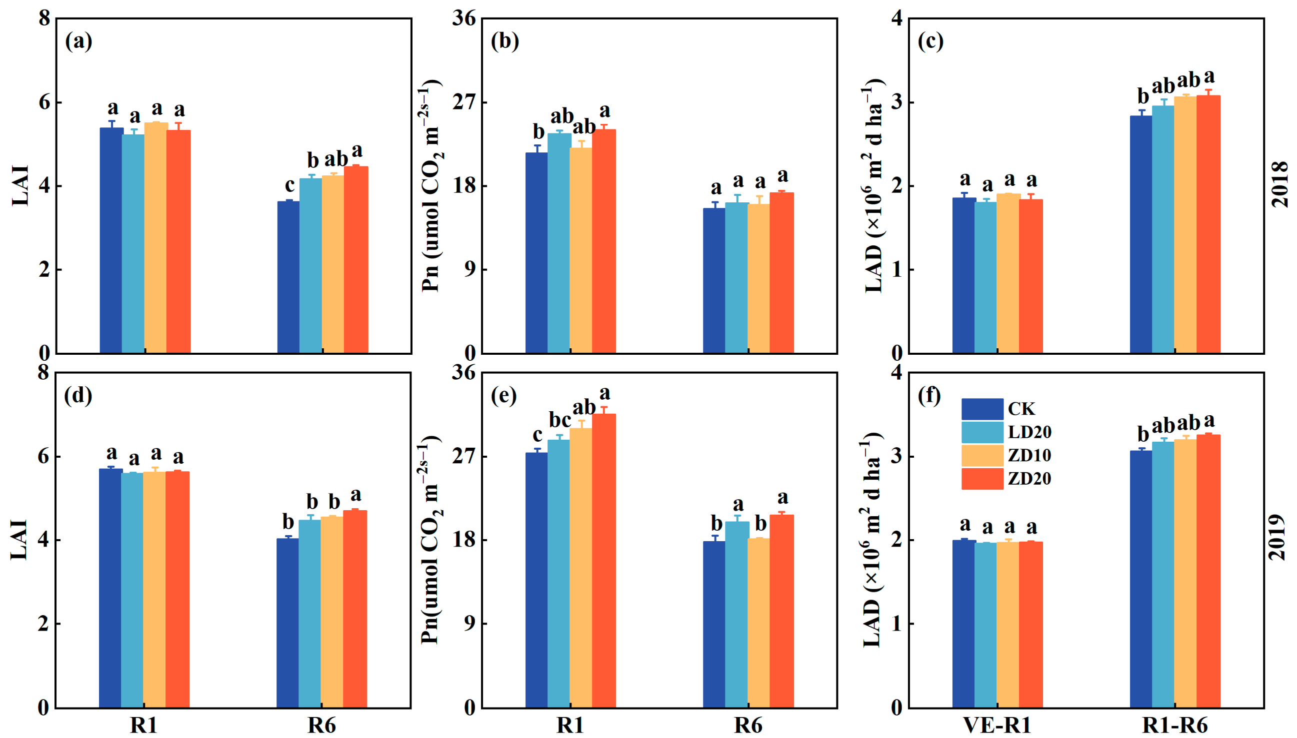

Figure 3. Leaf source characteristics of spring maize under different cultivation patterns in 2018 (**a**–**c**) and 2019 (**d**–**f**). Different letters indicate statistically significant differences at $p < 0.05$. Error bars indicate SEM (n = 3). LAI = leaf area index; Pn = net photosynthetic rate; LAD = leaf area duration. CK = linear planting with N fertilization at 10 cm depth, LD20 = linear planting with N fertilization at 20 cm depth, ZD10 = zigzag planting with N fertilization at 10 cm depth, and ZD20 = zigzag planting with N fertilization at 20 cm depth. VE = emergence; R1 = silking; R6 = maturity.

We found that LAD significantly increased ($p < 0.05$) by 6.3–8.7% only in ZD20 treatment. An increasing pattern of LAD was also observed in LD20 and ZD10 treatment, however, the increment was statistically insignificant compared to CK in all R1–R6 growth stages (Figure 3c,f). Additionally, no differences in LAD were found between the vegetative to reproductive (VE–R1) stages.

The photosynthetic rate (Pn) of leaves was found to be significantly ($p < 0.05$) increased in response to ZD10 and ZD20 treatments at the R1 stage overall. However, year-wise differences in Pn in response to treatments were observed, where ZD10 treatment was significantly ($p < 0.05$) increased by 9.5% only in 2019, ZD20 treatment showed a significant ($p < 0.05$) increase by 11.6% in 2018 and 15.3% in 2019 compared to CK in the respective years. We found no differences in the photosynthetic rate between CK and LD20 at the R1 stage throughout the study period. At the R6 stage, Pn was significantly ($p < 0.05$) higher in the ZD20 treatment followed by LD20, ZD10, and CK in the two-year experiment. However, separate year-wise analysis showed significant differences among treatments only in 2019. The Pn of leaves at the R6 stage of ZD20 and LD20 treatments was significantly increased ($p < 0.05$) by 14.2% and 12.2% compared to the ZD10 and CK treatments in 2019 (Figure 3b,e). This suggests that zigzag planting with deep nitrogen fertilization increased LAI, improved the photosynthetic rate at the R6 stage, and increased LAD throughout the R1–R6 stages, and the senescence of leaves was delayed in the late growth stages.

We found that the leaf angle (LA) and leaf orientation value (LOV) were overall significantly ($p < 0.05$) affected by the planting manner (P) (Table 1). We analyzed the leaf orientation value (LOV) and leaf angle (LA) of the upper, middle, and lower leaf of each sample maize plant across four treatments considering both years (2018 and 2019). In comparison to the CK treatment, the LA of the upper layer, middle layer, and bottom layer under three treatments, LD20, ZD10, and ZD20, was decreased, whereas LOV showed an increasing trend in contrast to LA (Table 1). The middle leaf angle was significantly ($p < 0.01$) affected by the year (Y). Compared to CK, the LA of the upper layer, middle layer, and whole plant under ZD10 treatment were significantly ($p < 0.05$) reduced by 16.8% (2019), 19.4% (2018), and 12.5% (2 years average), and the LOV of the middle layer, bottom layer, and whole plant under the ZD10 treatment were significantly increased 8.5%, 5.7% and 5.7% in 2018 ($p < 0.05$). There were no significant ($p = 0.071$–0.998) differences in the LA and LOV in each layer between the CK and LD20 treatments except for the LOV of the bottom layer under the LD20 treatment, which was significantly increased by 6.4% compared to CK in 2018 ($p < 0.05$). Compared to CK, the LA of the upper layer, middle layer, and whole plant under ZD20 treatment were significantly ($p < 0.05$) reduced by 17.2% (2019), 13.0% (2018), and 10.1% (two years average), and the LOV of the upper layer, middle layer, bottom layer, and whole plant were significantly ($p < 0.05$) increased by 9.3% (2019), 6.4% (2018), 8.0% (2018), and 5.7% (2018). This suggests that zigzag planting and deep N fertilization enhanced the LOV, which absorbed sufficient light and ventilation and eventually improved the canopy structure of maize.

3.3. Biomass Accumulation in Space and Time

Our result showed a substantial increase in maize biomass in all the improved planting strategies compared to traditional practices. We found significantly ($p < 0.05$) higher biomass accumulation in the ZD20 treatment, followed by ZD10 and LD20 compared to CK in both years (Figure 4).

The root biomass (0–30 cm depth) was found to be significantly ($p < 0.05$) increased by 4.4% and 7.4%, 17.1% and 21.7%, and 22.3% and 25.6% in response to LD20, ZD10, and ZD20 treatments compared to CK in 2018 and 2019, respectively. The stem biomass showed an increasing trend in response to LD20, ZD10, and ZD20 treatments compared to CK, however, the differences were statistically insignificant. The leaf biomass was significantly ($p < 0.05$) increased in response to LD20, ZD10, and ZD20 treatments compared to CK.

Table 1. Leaf angle (LA) and leaf orientation value (LOV) of spring maize under different cultivation patterns.

Treatment		Leaf Angle (°) (LA)				Leaf Orientation Value (LOV)			
		Upper Leaf	Middle Leaf	Lower Leaf	Average of Total	Upper Leaf	Middle Leaf	Lower Leaf	Average of Total
2018	CK	20.96 ± 1.54 a	29.01 ± 0.71 a	29.16 ± 0.21 a	26.37 ± 0.56 a	68.10 ± 0.84 a	48.20 ± 0.65 c	40.45 ± 0.89 b	52.25 ± 0.44 c
	LD20	20.39 ± 0.78 a	26.20 ± 1.09 ab	27.75 ± 0.76 a	24.78 ± 0.45 ab	68.34 ± 0.60 a	48.85 ± 0.99 bc	43.05 ± 0.45 a	53.41 ± 0.52 bc
	ZD10	18.16 ± 1.59 a	23.37 ± 0.13 b	27.35 ± 1.10 a	22.96 ± 0.74 b	70.67 ± 0.75 a	52.32 ± 0.87 a	42.71 ± 0.34 a	55.23 ± 0.46 a
	ZD20	20.21 ± 0.40 a	25.24 ± 1.38 b	26.30 ± 1.14 a	23.92 ± 0.90 b	69.09 ± 0.88 a	51.30 ± 0.43 ab	43.68 ± 0.80 a	54.69 ± 0.64 ab
2019	CK	21.46 ± 0.83 a	24.52 ± 1.23 a	29.80 ± 2.00 a	25.26 ± 1.28 a	66.08 ± 2.28 b	49.08 ± 4.11 a	41.85 ± 2.81 a	52.34 ± 2.92 a
	LD20	21.46 ± 0.68 a	23.70 ± 1.25 a	29.19 ± 0.53 a	24.78 ± 0.47 ab	67.60 ± 1.30 ab	49.94 ± 2.33 a	43.56 ± 0.38 a	53.70 ± 1.23 a
	ZD10	17.85 ± 0.30 b	22.87 ± 0.70 a	25.90 ± 0.96 a	22.21 ± 0.44 bc	70.04 ± 0.79 ab	51.49 ± 1.14 a	46.27 ± 0.49 a	55.94 ± 0.58 a
	ZD20	17.77 ± 1.17 b	22.27 ± 0.76 a	27.54 ± 1.24 a	22.52 ± 0.26 c	72.23 ± 1.17 a	53.90 ± 1.47 a	43.68 ± 0.33 a	56.61 ± 0.76 a
ANOVA Year (Y)		NS	14.09 **	NS	NS	NS	NS	NS	NS
Planting (P)		12.73 **	12.07 **	7.84 *	23.04 ***	12.57 **	5.94 *	5.48 *	9.60 **
N depth (D)		NS	NS	NS	NS	NS	NS	NS	NS
P × D		NS	NS	NS	NS	NS	NS	NS	NS
Y × P × D		NS	NS	NS	NS	NS	NS	NS	NS

Different letters indicate statistically significant differences at $p < 0.05$. Error bars indicate SEM ($n = 3$). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. NS = no significance. CK = linear planting with N fertilization at 10 cm depth, LD20 = linear planting with N fertilization at 20 cm depth, ZD10 = zigzag planting with N fertilization at 10 cm depth, and ZD20 = zigzag planting with N fertilization at 20 cm depth.

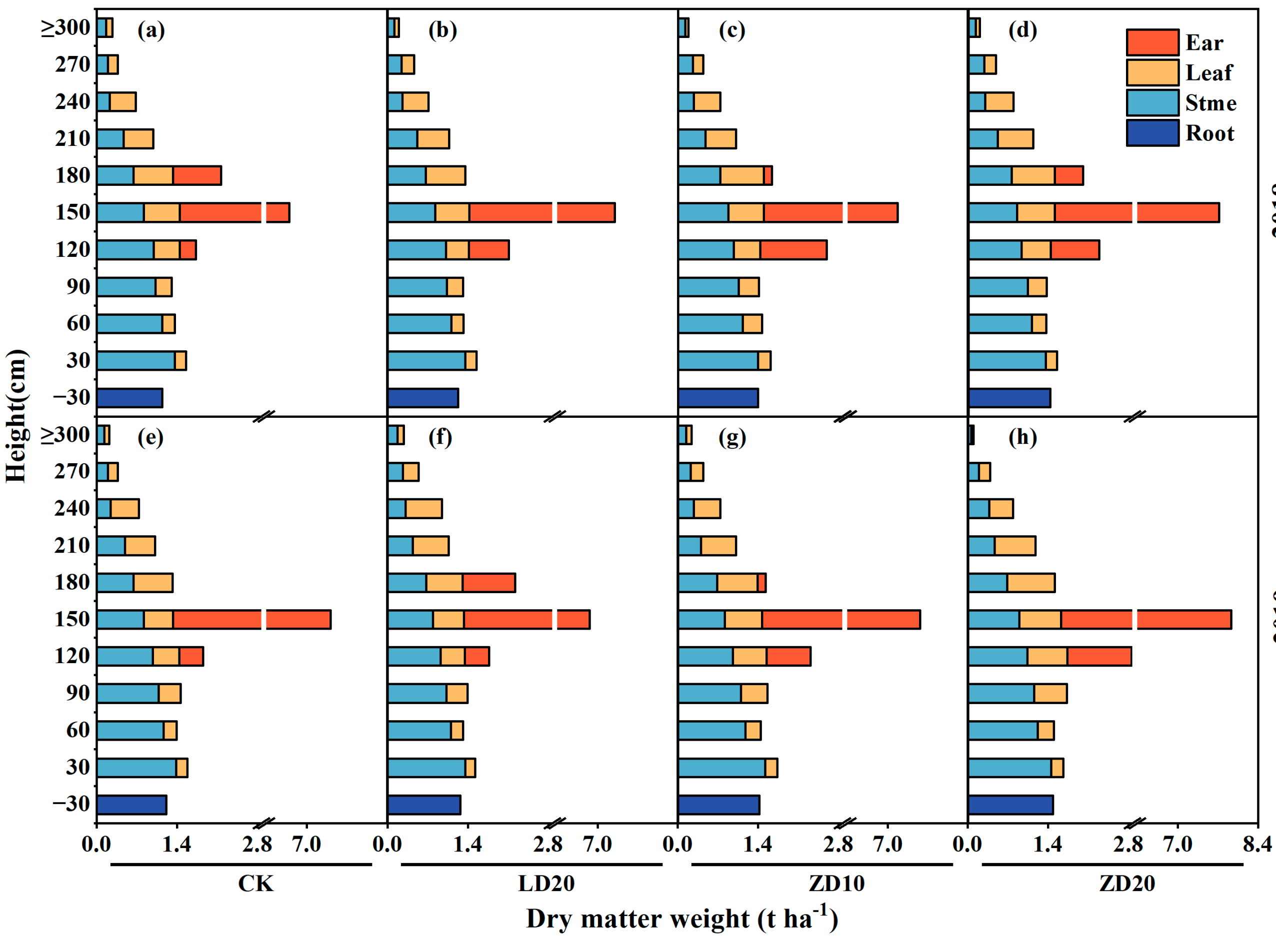

Figure 4. Vertical distribution of the canopy biomass under different cultivation patterns. (**a**,**e**) CK = linear planting with N fertilization at 10 cm depth, (**b**,**f**) LD20 = linear planting with N fertilization at 20 cm depth, (**c**,**g**) ZD10 = zigzag planting with N fertilization at 10 cm depth, and (**d**,**h**) ZD20 = zigzag planting with N fertilization at 20 cm depth.

Furthermore, we compared the leaf biomass of CK to LD20, ZD10, and ZD20 treatments in three layers (upper, middle, and bottom, see the methods for detail) of the plants. Leaf biomass under LD20 treatment was increased by 3.2% and 3.6%, decreased by 4.7% and 2.8%, and decreased by 0.6% and 6.4% in the upper, middle, and bottom layers in 2018 and 2019, respectively. Leaf biomass under ZD10 treatment in upper, middle, and bottom layers was decreased by 3.4% and increased by 2.8%, increased by 4.1% and 17.8%, and increased by 34.0% and 18.2% in 2018 and 2019, respectively. Leaf biomass under ZD20 treatment was increased by 5.8% and decreased by 3.6%, increased by 8.7% and 37.3%, and increased by 12.5% and 32.2% in the upper, middle, and bottom layers in 2018 and 2019, respectively. The ear biomass under LD20, ZD10, and ZD20 treatments were increased by 3.2% and 5.5%, 7.7% and 9.2%, and 14.0% and 18.3%, respectively, compared to CK in 2018 and 2019, respectively. Zigzag planting (ZD10 and ZD20) treatments promoted the development of the middle leaves and improved the proportion of biomass in the middle layer of the population compared to linear planting treatments (CK and LD20).

We further compared the biomass in the different growing stages of maize among the treatments and year (Table 2). We found that the root biomass was significantly ($p < 0.05$) affected by the year (Y). The root biomass, shoot biomass at the R6 stage, and biomass accumulation after the R1 stage were significantly ($p < 0.05$) affected by the planting manner (P). The shoot biomass at the R6 stage and biomass accumulation after the R1 stage were significantly ($p < 0.05$) affected by the N depth (D) (Table 2). In the R1 stage, the biomass of both root and shoot increased under ZD10 and ZD20 treatments, whereas LD20 treatment increased only the root biomass. However, the differences between the treatments were insignificant statistically. In the R6 stage, the biomass of shoot and root was found to be highest in ZD20 followed by ZD10, LD20, and CK. Compared to CK, the shoot biomass under ZD10 and ZD20 treatments was significantly ($p < 0.05$) increased by 8.8% and 10.3%, and 12.9% and 16.1%, respectively, in 2018 and 2019. Similarly, the root biomass was significantly ($p < 0.05$) increased by 21.5% and 21.9%, and 27.1% and 25.4%. LD20 increased the shoot biomass of CK by 6.3% ($p = 0.050$) and 5.2% ($p = 0.260$), the root biomass was increased by 0.9% ($p = 0.890$) and 7% ($p = 0.318$), respectively, in 2018 and 2019; however, the difference among the treatments was insignificant. Further, in the same depth N fertilization treatments, the biomass of shoot and root in zigzag planting (ZD10 and ZD20) was significantly ($p < 0.05$) higher than that of linear planting (CK and LD 20). The biomass accumulation and accumulation rate were found to be highest in ZD20 followed by ZD10 and LD20 compared to CK after the R1 stage. Specifically, the biomass accumulation of ZD20 treatment increased significantly ($p < 0.05$) by 21.9% and 28.0% in 2018 and 2019, respectively. In the pre-silking and post-silking stages, the biomass accumulation significantly ($p < 0.05$) increased in 2019 compared to 2018 after the R1 stage.

Table 2. Biomass accumulation and accumulation rate before and after silking of spring maize under different cultivation patterns.

Year	Treatment	R1		R6		Before R1		After R1	
		Shoot Biomass (t ha^{-1})	Root Biomass (t ha^{-1})	Shoot Biomass (t ha^{-1})	Root Biomass (t ha^{-1})	Biomass Accumulation (t ha^{-1})	Accumulation Rate (%)	Biomass Accumulation (t ha^{-1})	Accumulation Rate (%)
2018	CK	8.83 ± 0.25 a	1.31 ± 0.03 a	21.17 ± 0.84 c	1.07 ± 0.03 b	10.14 ± 0.27 a	0.46 ± 0.03 a	12.10 ± 1.10 b	0.54 ± 0.03 b
	LD20	8.81 ± 0.27 a	1.36 ± 0.06 a	22.50 ± 0.74 b	1.08 ± 0.11 b	10.17 ± 0.33 a	0.43 ± 0.03 b	13.41 ± 1.15 ab	0.57 ± 0.03 a
	ZD10	9.00 ± 0.13 a	1.41 ± 0.09 a	23.03 ± 0.47 ab	1.30 ± 0.06 a	10.42 ± 0.22 a	0.43 ± 0.00 b	13.91 ± 0.31 ab	0.57 ± 0.00 a
	ZD20	9.11 ± 0.25 a	1.42 ± 0.08 a	23.91 ± 0.71 a	1.36 ± 0.10 a	10.53 ± 0.32 a	0.42 ± 0.03 b	14.75 ± 1.11 a	0.58 ± 0.03 a
2019	CK	9.01 ± 0.34 a	1.41 ± 0.05 a	21.69 ± 0.82 c	1.14 ± 0.06 b	10.41 ± 0.38 a	0.46 ± 0.01 a	12.42 ± 0.71 b	0.54 ± 0.01 b
	LD20	9.13 ± 0.50 a	1.43 ± 0.11 a	22.81 ± 1.36 bc	1.22 ± 0.12 b	10.56 ± 0.56 a	0.44 ± 0.01 a	13.47 ± 1.01 b	0.56 ± 0.01 b
	ZD10	9.38 ± 0.47 a	1.52 ± 0.06 a	23.92 ± 1.22 ab	1.38 ± 0.07 a	10.90 ± 0.53 a	0.43 ± 0.04 a	14.41 ± 1.79 ab	0.57 ± 0.04 b
	ZD20	9.18 ± 0.89 a	1.55 ± 0.11 a	25.19 ± 1.06 a	1.43 ± 0.07 a	10.73 ± 1.00 a	0.40 ± 0.02 b	15.90 ± 0.31 a	0.60 ± 0.02 a
ANOVA Year (Y)		NS	9.58 **	NS	7.15 *	NS	NS	NS	NS
Planting (P)		NS	9.20 **	26.23 ***	50.10 ***	NS	6.72 *	19.68 ***	6.72 *
N depth (D)		NS	NS	8.90 **	NS	NS	7.55 *	NS	NS
P × D		NS	NS	NS	NS	NS	NS	NS	NS
Y × P × D		NS	NS	NS	NS	NS	NS	NS	NS

Different letters indicate statistically significant differences at $p < 0.05$. Error bars indicate SEM ($n = 3$). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. NS = no significance. CK = linear planting with N fertilization at 10 cm depth, LD20 = linear planting with N fertilization at 20 cm depth, ZD10 = zigzag planting with N fertilization at 10 cm depth, and ZD20 = zigzag planting with N fertilization at 20 cm depth. VE = emergence; R1 = silking; R6 = maturity.

3.4. Soil Physicochemical Properties

The physicochemical properties of the 0–20 cm soil layer were analyzed after the maize harvest. The NH_4^+-N, NO_3^--N AP, and AK were found to be significantly ($p < 0.05$) affected by the year (Y), planting manner (P), N depth (D), and their interaction (P × D and Y × P × D) (Y effect on AK, P effect on NH_4^+-N, P × D effect on NH_4^+-N and AK, and Y × P × D effect on NH_4^+-N were found to be insignificant) (Table S2). We found no significant difference in soil water content (SWC) ($p = 0.072$, $p = 0.174$), and total carbon (TC) ($p = 0.156$, $p = 0.336$) across the treatments compared to CK in 2018 and 2019, respectively (Figure 5a,d). NH_4^+-N content was significantly decreased in soil by 15.5% ($p < 0.05$) and 9.9% ($p = 0.063$); 3.1% ($p = 0.664$) and 4.2% ($p = 0.408$); and 23.2% ($p < 0.05$) and 14.8% ($p < 0.05$) in response to LD20, ZD10, and ZD20 compared to CK in 2018 and 2019, respectively, (Figure 5b). NO_3^--N content was significantly ($p < 0.05$) decreased in soil by 43.4% and 23.7%; 52.5% and 35.7%; and 58.6% and 40.2% in response to LD20, ZD10, and ZD20 treatments compared to CK in 2018 and 2019, respectively (Figure 5c). We found that a combination of zigzag planting and deep nitrogen fertilization decreased the NH_4^+-N and NO_3^--N contents. The AP content was significantly ($p < 0.05$) decreased by 35.4% and 29.2%; 22.3% and 26.0%; and 53.5% and 40.0% under LD20, ZD10, and ZD20 treatment compared to CK in 2018 and 2019, respectively (Figure 5e). The AK content was significantly decreased by 2.1% ($p = 0.313$) and 4.9% ($p < 0.05$); 10.5% ($p < 0.05$) and 4.7% ($p < 0.05$); and 11.2% ($p < 0.05$) and 11.1% ($p < 0.05$) under LD20, ZD10, and ZD20 treatments compared to CK (Figure 5f). Soil physiochemical characteristics measurement showed that zigzag planting and deep nitrogen fertilizer decreased the contents of NH_4^+-N, NO_3^--N, AP, and AK, suggesting higher nutrient absorption by plants.

3.5. Yield and Correlation Analysis

The results of the ANOVA analysis showed that the year (Y) and planting manner (P) had significant ($p < 0.05$) effects on the yield and yield components. However, the Y effects on effective ear and P effects on 1000-kernel weight were found to be statistically insignificant (Table 3). Our result showed that zigzag planting increased the number of panicles, however, the difference among treatments was statistically insignificant ($p = 0.077$, $p = 0.324$) (Table 3). The yield was significantly ($p < 0.001$) affected by the N depth (D). The kernel number was found to be produced highest in ZD20 followed by ZD10, LD20, and CK. The grain number per panicle of ZD10 and ZD20 treatments in both years was significantly ($p < 0.05$) higher than CK in respective years. We did not find a significant difference in the 1000-grain weight among treatments. Comparing the yield of CK, the highest yield was found in the ZD20 (10.0% and 14.4%) treatment followed by ZD10 (6.2–10.4%), LD20 (4.7–6.6%) in 2018 and 2019, respectively. The yield of zigzag planting (ZD10 and ZD20) was significantly ($p < 0.05$) higher than linear planting (CK and LD20) under the same depth of N fertilization. Considering the same planting manner, the yield was significantly ($p < 0.05$) higher at 20 cm N fertilization depth than at 10 cm depth. In contrast, the yield between ZD10 and ZD20 treatments was not significantly different in 2019. The yield traits yield, kernels per spike, and 1000-seed weight were higher in 2019 than in 2018.

The correlation analysis was conducted between the dry matter accumulation, leaf source characteristics, soil nutrient, and yield (AY) (Figure 6). We found that matured root dry weight (MR) was negatively correlated with nitrate nitrogen (NN) and available potassium (AK) (RMRNN ** = −0.70, RMRAK ** = −0.69). Before the silking stage, dry matter accumulation (BS) was positively correlated with silking root dry weight (SR), maturity root dry weight (MR), and maturity leaf area index (ML) (RBSSR ** = 0.80; RBSMR ** = 045, RBSML ** = 0.43). After silking, dry matter accumulation (AS) was positively correlated with silking root dry weight (SR), maturity root dry weight (MR), maturity leaf area index (ML), and after silking leaf area duration (AL) (RASSR ** = 0.62, RASMR ** = 0.67, RASML ** = 0.78, RASAL * = 0.42). Yield (AY) was negatively correlated with ammonia nitrogen (AN), nitrate nitrogen (NN), available phosphorus (AP), and available potassium (AK) (RAYAN ** = −0.58, RAYNN ** = −0.77, RAYAP ** = −0.83, RAYAK ** = −0.75). However, yield (AY) was positively correlated with maturity root dry weight (MR), after silking dry matter accumulation (AS), maturity leaf area index (ML), after silking leaf area duration (AL), silking net photosynthetic rate (SN), and maturity net photosynthetic rate (MN) (RAYMR ** = 0.57, RAYAS ** = 0.67, RAYML ** = 0.54, RAYAL ** = 0.74, RAYSN * = 0.50, RAYMN * = 0.43).

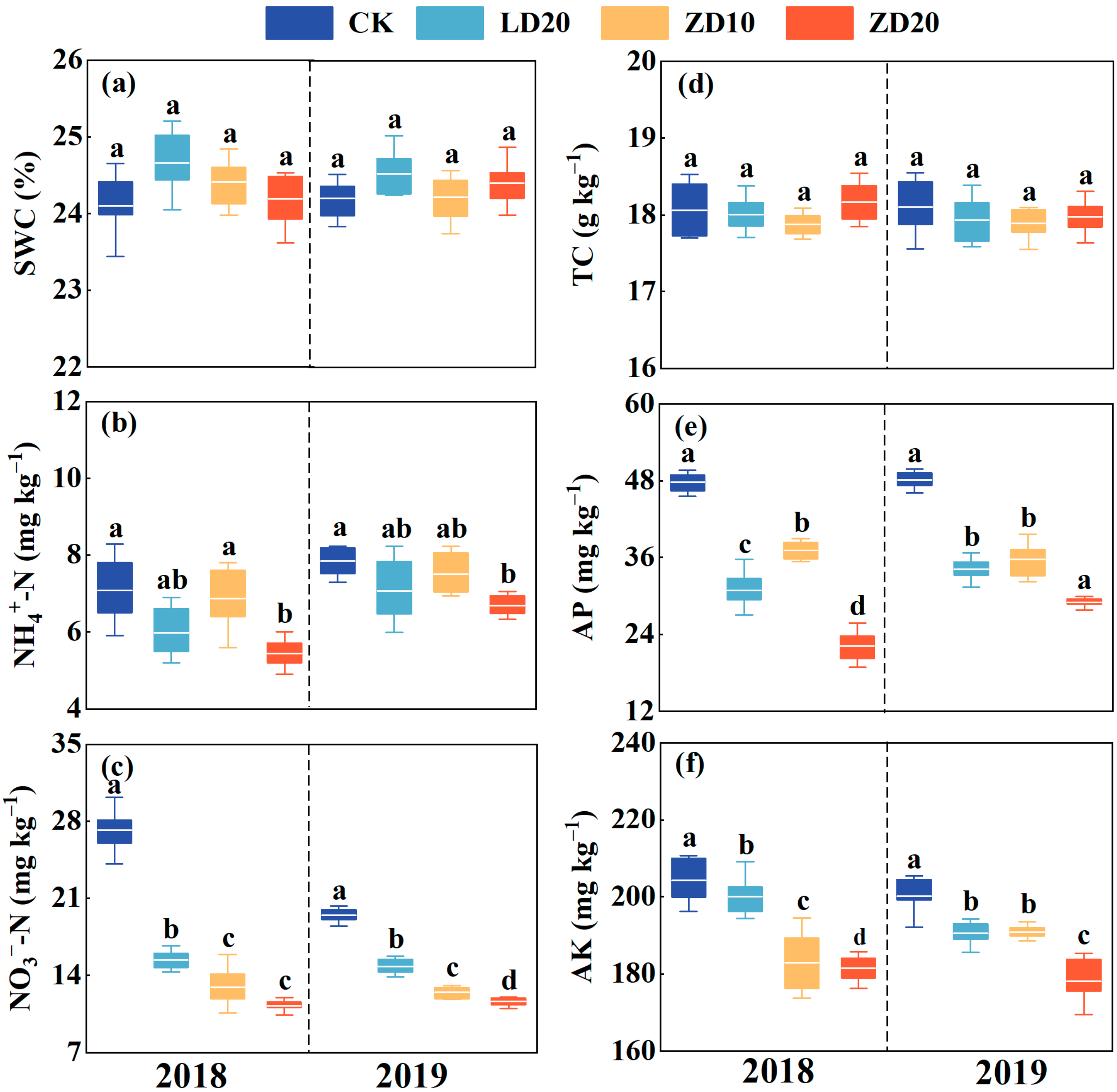

Figure 5. Effect of different cultivation patterns on soil properties after harvest in 2018 and 2019. Different letters indicate statistically significant differences at $p < 0.05$. Error bars indicate SEM ($n = 5$). (**a**) SWC = soil water content; (**b**) NH_4^+-N = ammonium nitrogen; (**c**) NO_3^--N = nitrate nitrogen; (**d**) TC = total carbon; (**e**) AP = available phosphorus; (**f**) AK = available potassium. CK = linear planting with N fertilization at 10 cm depth, LD20 = linear planting with N fertilization at 20 cm depth, ZD10 = zigzag planting with N fertilization at 10 cm depth, and ZD20 = zigzag planting with N fertilization at 20 cm depth.

Table 3. Spring maize yield and its components under different cultivation patterns.

Year	Treatment	Effective Ear ($\times 10^4$ ear ha^{-1})	Kernel Number (ear^{-1})	1000-Kernel Weight (g)	Yield (t ha^{-1})
2018	CK	6.70 ± 0.05 ab	499.92 ± 11.4 b	343.21 ± 5.09 a	9.53 ± 0.12 c
	LD20	6.67 ± 0.06 b	509.25 ± 5.02 ab	347.48 ± 1.52 a	9.98 ± 0.07 b
	ZD10	6.73 ± 0.06 ab	518.42 ± 2.75 a	345.11 ± 1.77 a	10.12 ± 0.24 b
	ZD20	6.80 ± 0.05 a	522.00 ± 8.51 a	343.99 ± 8.88 a	10.48 ± 0.07 a
2019	CK	6.60 ± 0.10 a	511.08 ± 4.02 b	351.74 ± 2.22 a	9.58 ± 0.16 c
	LD20	6.68 ± 0.08 a	513.42 ± 4.30 b	353.17 ± 1.15 a	10.21 ± 0.33 b
	ZD10	6.72 ± 0.10 a	534.08 ± 12.98 a	353.07 ± 0.90 a	10.58 ± 0.25 ab
	ZD20	6.75 ± 0.10 a	542.50 ± 14.98 a	350.96 ± 2.53 a	10.96 ± 0.25 a
ANOVA Year (Y)		NS	12.01 **	20.62 ***	13.12 **
Planting (P)		7.60 *	31.44 ***	NS	71.51 ***
N depth (D)		NS	NS	NS	29.87 ***
P × D		NS	NS	NS	NS
Y × *P × *D		NS	NS	NS	NS

Different letters indicate statistically significant differences at $p < 0.05$. Error bars indicate SEM ($n = 3$). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. NS = no significance. CK = linear planting with N fertilization at 10 cm depth, LD20 = linear planting with N fertilization at 20 cm depth, ZD10 = zigzag planting with N fertilization at 10 cm depth, and ZD20 = zigzag planting with N fertilization at 20 cm depth.

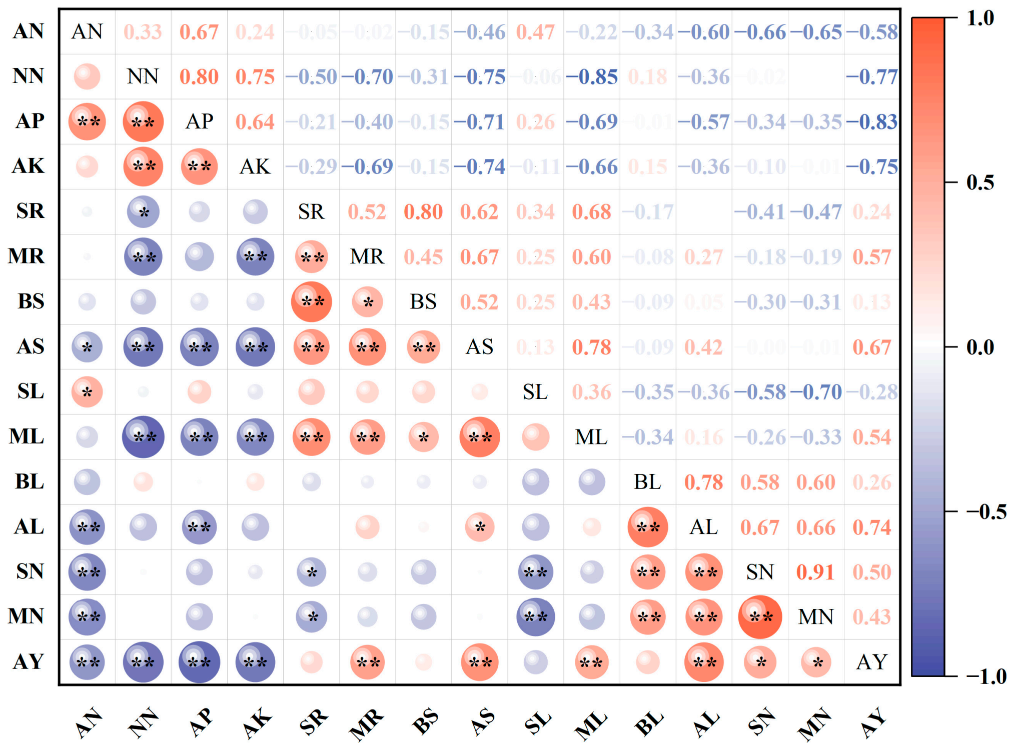

Figure 6. Pearson correlation coefficients of soil properties, dry matter accumulation, leaf source characteristics, and yield under different cultivation patterns. * = significant at the 5% probability level; ** = significant at the 1% probability level; AN = ammonia nitrogen; NN = nitrate nitrogen; AP = available phosphorus; AK = available potassium; SR = silking root dry weight; MR = maturity root dry weight; BS = before silking dry matter accumulation; AS = after silking dry matter accumulation; SL = silking leaf area index; ML = maturity leaf area index; BL = before silking leaf area duration; AL = after silking leaf area duration; SN = silking net photosynthetic rate; MN = maturity net photosynthetic rate; AY = yield. The red circle represents the positive correlation between the two variables, the blue represents the negative correlation, and the size of the circles represent the strength of the correlation.

4. Discussion

China has a high demand for maize due to insufficient production in its limited arable land [9]. Maize production primarily depends on planting manner and nutrient availability [48,49]. Therefore, improving these two aspects is essential to substantially increase the maize yield and fulfill the demand. In our study, we employed linear and zigzag planting manners with nutrient fertilization at different depths to increase maize yield. We measured changes in root distribution, leaf characteristics, soil characteristics, biomass of root, shoot, and grain and yield with respect to different treatments. Our study revealed that zigzag planting and deep nitrogen fertilization increased the yield. However, using a combination of both strategies showed a significant increment in maize yield compared to singly applied improvement strategies. The root system (i.e., morphology, distribution, and physiological ability) forms the basis of growth by absorbing more nutrition and moisture, thereby enhancing the maize yield [50–53].

In this study, we observed a significant difference in root length density based on the planting manner (P) and N at different depths (D). Specifically, we found that root length density increased significantly in the 10–30 cm soil layer with linear planting and N fertilization at 20 cm depth (LD20), and this result is consistent with a study by York et al. [54] in the USA, where deep nitrogen fertilization was found to increase the root length density in maize. Additionally, our study results were consistent with studies by Jiang et al. [12] and Zhang et al. [25], where zigzag planting manner was found to increase the root length density. These studies are similar to our linear planting at 20 cm depth and zigzag planting treatments, and resulted in maize root length density increment. Zigzag planting changed the row spacing, which can regulate root growth and optimize spatial root distribution [25]. In zigzag planting, the root grows and reaches deep soil layers, which allows for the utilization of more space moisture, and nutrients that improve the growth and resistance of maize against pest, pathogen, and environmental extremities [55,56]. Compared to CK, we found that the root length density increased substantially in the ZD10 and ZD20 treatments in each soil layer (10–40 cm), especially in the deep layers in the maturity stage (Figure 2, Table 2), which benefited from the increased root activities, delayed the senescence of the roots after silking stage (R1–R6), and maintained the supply of nutrition and moisture of the root system to above-ground during the late growth period.

We further explored soil nutrients in different soil layers and found that nitrate nitrogen (NN), and available potassium (AK) were negatively correlated with root dry weight at the maturity stage in soil after harvest at 0–20 cm depth. Moreover, our results showed that ammonia nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), available phosphorus (AP), and available potassium (AK) content were substantially lower in LD20, ZD10, and ZD20 treatments than CK in the 0–20 cm soil layer (Figure 6). These finding suggests that the nutrients were absorbed by the maize, resulting in substantially lower nutrient content than traditional cultivating practice (CK) in soil. This further indicates that deep placement of N fertilizer and zigzag planting considerably promoted the growth and ability of the root system to absorb nutrients.

As root distribution, the development of above-ground parts (i.e., stem characteristics) of maize is equally important to enhance the yield [41]. The root system absorbs water and nutrients, which are then transported to the above-ground parts. Above-ground parts synthesize organic matter and then supply it to roots, demonstrating the frequent exchanges of material and energy to promote the overall plant growth [56]. In our study, we found that planting manners have considerable effect on the photosynthetic parameters. The above ground characteristic—the stem angle—significantly reduced in the middle to upper part of the maize plants (Table 1), which substantially promoted the growth of the middle part of the leaves in zigzag treatments (ZD10 and ZD20) (Figure 4). The zigzag planting altered the distance between the adjacent plants, thus the compact upper leaves reduced the plant population's shade, which benefited the light penetration in the middle and lower leaves. The higher light interception rate in the middle and lower leaves [57] substantially increased the net photosynthetic rate (Pn) at the silking stage

(R1), leaf area duration (LAD) after the silking stage, and leaf area index (LAI) at the maturity stage in response to LD20, ZD10, and ZD20 treatments (Figure 3) in both years. Furthermore, we found a positive correlation of dry matter accumulation with leaf area duration after the silking stage and leaf area index at the maturity stage (Figure 6). These leaf characteristics showed higher photosynthetic potential and photosynthetic rate at the late growth period, which is favorable for obtaining more photosynthesis product and transporting it into maize grains [14]. The weight of the root and above-ground dry matter enhanced the dry matter accumulation rate after the silking stage in response to LD20, ZD10, and significantly in ZD20 compared to CK. This suggests that zigzag planting alters the growth state of plant leaves and optimizes the canopy structure. Deep nitrogen fertilization and zigzag planting singly and in combination delayed the senescence of the leaf, stimulated photosynthesis, synthesized more photosynthesis product, and eventually increased the yield of maize [25,48,58].

The improvement in yield is a result of the coordination of the individual and population plants effect [13]. At the maturity stage, we found a positive correlation of yield with root dry weight and leaf area index, leaf area duration after silking stage, and the net photosynthetic rate at the silking and maturity stage (Figure 6). Our research shows that both deep nitrogen fertilization and zigzag planting either singly or in combination substantially increased the yield. Compared to CK, the yield increased by 4.7% (2018) and 6.6% (2019) in the LD20 treatment, increased by 6.2% (2018) and 10.4% (2019) in the ZD10 treatment, and the highest increment by 10.0% (2018) and 14.4% (2019) in the ZD20 treatment (Table 3). This indicates that yield could be further increased by combining deep nitrogen fertilization with zigzag planting. When we compared yield between two years, we found that the yield in 2019 was higher than in 2018, which may be related to 44.6% higher precipitation after the silking stage in 2019 than in 2018 (Figure S1). The silking-filling stage is critical for maize as maximum water is required at this stage compared to the other stages of maize. At this stage, abundant rainfall can ensure the normal flowering and powdering of maize, increasing the bearing rate, promoting grain filling, and increasing the yield [59,60]. In a drought year (2018), the yield of the two treatments of zigzag planting increased by an average of 8.1% compared to linear planting, indicating that zigzag planting improved the resource utilization efficiency of the maize population. Additionally, we found a significantly positive correlation of yield with the photosynthetic rate at the silking stage and maturity stage, the dry matter accumulation, photosynthetic potential after silking stage, root dry matter, and leaf area index at the maturity stage (Figure 6). This suggests that maintaining root system development after the silking stage and ensuring adequate nutrient and moisture supply are prerequisites for the yield, which was achieved in our study. The main reasons for the increase in yield were delaying the leaf senescence after the silking stage, maintaining the accumulation ability of dry matter, and achieving effective coordination of the root–shoot.

Our study provides evidence for the effectiveness of existing maize planting strategies: deep nitrogen fertilization and zigzag planting for improving maize yield by maintaining the root–shoot characteristics, as we predicted in our first and second hypotheses. We also proposed that the combination of deep nitrogen fertilization and zigzag planting could be a more effective method as this combines the advantages of both strategies. Our results confirmed this as we found significant enhancement in the maize yield, supporting our third hypothesis. The combined (ZD20) method of maize cultivation has the potential to not only enhance the yield, but also contribute to the commercial mass production of maize and ensure food security on a national level.

5. Conclusions

We studied the effectiveness of existing (CK, LD20, and ZD10) and improved (ZD20) maize cultivation strategies in order to enhance maize yield. Our results demonstrated that zigzag planting and nitrogen supplementation at deep soil layers (LD20, ZD10, and ZD20) outperformed the yield compared to traditional cultivating methods in both years of our study. Furthermore, zigzag planting with deep nitrogen fertilization (ZD20) significantly improved the yield compared to existing strategies. Zigzag planting allows for reduced competition among plants for moisture and nutrient absorption by increasing the space needed to spread roots and optimizing the canopy structure and leaf area duration by altering the growth state of the leaves. In addition, the application of nitrogen fertilizer at the deep soil layer provided additional nutritional resources that promoted root growth, delayed plants senescence, and increased leaf photosynthesis during the late growth period. As such, these proposed maize planting strategies could be highly beneficial for farmers from local and global levels, contributing to food security in countries where maize is a staple food. In China, where maize is grown on a large scale, these improved planting strategies could increase the production without the need for land expansion, thereby preserving the productivity of other crops. These improved strategies could also be applied to other crops that face similar problems and have a similar growing mechanism as maize.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13051307/s1, Figure S1: Precipitation and mean temperature during the growing seasons for maize. Table S1: Variance analysis of leaf source characteristics of spring maize under different cultivation patterns (F value). Table S2: Variance analysis of soil properties after harvest under different cultivation patterns (F value).

Author Contributions: Y.Z., Y.J. and H.Q. designed the study; Y.Z. performed the study, Y.Y., C.L., Y.W., H.Z., H.R. and X.G. contributed reagents/materials/analysis tools and analyzed the data; Y.Z., Y.J. and H.Q. wrote the paper. All authors have read and agreed to the published version of the manuscript.

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References

1. Sheng, Y.; Song, L.G. Agricultural production and food consumption in China: A long-term projection. *China Econ. Rev.* **2019**, *53*, 15–29. [CrossRef]
2. The State Statistical Bureau of the People's Republic of China. *China Statistical Yearbook*; China Statistics Press: Beijing, China, 2021.
3. The State Statistical Bureau of the People's Republic of China. *Announcement of Grain Yield Data in 2021 According to Bulletin of the State*; Statistical Bureau of the People's Republic of China: Beijing, China, 2021.
4. The State Statistical Bureau of the People's Republic of China. *Announcement of Grain Yield Data in 2022 According to Bulletin of the State*; Statistical Bureau of the People's Republic of China: Beijing, China, 2022.
5. Yu, Y.; Feng, K.S.; Hubacek, K.; Sun, L.X. Global implications of China's future food on consumption. *J. Ind. Ecol.* **2016**, *20*, 593–602. [CrossRef]
6. The State Statistical Bureau of the People's Republic of China. *Main Data Bulletin of the Third National Land Resource Survey*; National Bureau of Statistics: Beijing, China, 2021.
7. Liu, T.N.; Chen, J.Z.; Wang, Z.Y.; Wu, X.R.; Wu, X.C.; Ding, R.X.; Han, Q.F.; Cai, T.; Jia, Z.K. Ridge and furrow planting pattern optimizes canopy structure of summer maize and obtains higher grain yield. *Field Crop. Res.* **2018**, *219*, 242–249. [CrossRef]
8. Liu, T.D.; Song, F.B.; Liu, S.Q.; Zhu, X.C. Light interception and radiation use efficiency response to narrow-wide row planting patterns in maize. *Aust. J. Crop Sci.* **2012**, *6*, 506–513.
9. Piao, L.; Zhang, S.Y.; Yan, J.Y.; Xiang, T.X.; Chen, Y.; Li, M.; Gu, W.R. Contribution of fertilizer, density and row spacing practices for maize yield and efficiency enhancement in Northeast China. *Plants* **2022**, *11*, 2985. [CrossRef] [PubMed]

10. Chen, Y.L.; Xiao, C.X.; Wu, D.L.; Xia, T.T.; Chen, Q.W.; Chen, F.J.; Yuan, L.X.; Mi, G.H. Effects of nitrogen application rate on grain yield and grain nitrogen concentration in two maize hybrids with contrasting nitrogen remobilization efficiency. *Eur. J. Agron.* **2015**, *62*, 79–89. [CrossRef]
11. Bernhard, B.J.; Below, F.E. Plant population and row spacing effects on corn: Plant growth, phenology, and grain yield. *Agron. J.* **2020**, *112*, 2456–2465. [CrossRef]
12. Jiang, C.Q.; Lu, D.J.; Zu, C.L.; Shen, J.; Wang, S.J.; Guo, Z.B.; Zhou, J.M.; Wang, H.Y. One-time root-zone N fertilization increases maize yield, NUE and reduces soil N losses in lime concretion black soil. *Sci. Rep.* **2018**, *8*, 10258. [CrossRef] [PubMed]
13. Bernhard, B.J.; Below, F.E. Plant population and row spacing effects on corn: Phenotypic traits of positive yield-responsive hybrids. *Agron. J.* **2020**, *112*, 1589–1600. [CrossRef]
14. Liu, T.D.; Song, F.B. Maize photosynthesis and microclimate within the canopies at grain-filling stage in response to narrow-wide row planting patterns. *Photosynthetica* **2012**, *50*, 215–222. [CrossRef]
15. Liu, S.Q.; Jian, S.L.; Li, X.N.; Wang, Y. Wide–narrow row planting pattern increases root lodging resistance by adjusting root architecture and root physiological activity in maize (*Zea mays* L.) in Northeast China. *Agriculture* **2021**, *11*, 517. [CrossRef]
16. Liu, C.W.; Zhang, E.H.; Xie, R.Z.; Liu, W.R.; Li, S.K. Effect of different nitrogen supply methods on yield and photosynthesis of maize under the alternative fallow high stubble about narrow row and wide row. *Acta Pratacult. Sin.* **2012**, *21*, 34–42.
17. Wu, K.; Zhou, F.; Zhou, S.; Zhang, X.; Wu, B. Enhancing root lodging resistance of maize with twin plants in wide-narrow rows: A case study. *Plant Prod. Sci.* **2020**, *23*, 286–296. [CrossRef]
18. Gao, J.; Lei, M.; Yang, L.J.; Wang, P.; Tao, H.B.; Huang, S.B. Reduced row spacing improved yield by optimizing root distribution in maize. *Eur. J. Agron.* **2021**, *127*, 126291. [CrossRef]
19. Lauer, J.G.; Rankin, M. Corn response to within row plant spacing variation. *Agron. J.* **2004**, *96*, 1464–1468. [CrossRef]
20. Balkcom, K.S.; Satterwhite, J.L.; Arriaga, F.J.; Price, A.J.; Van Santen, E. Conventional and glyphosate-resistant maize yields across plant densities in single-and twin-row configurations. *Field Crop. Res.* **2011**, *120*, 330–337. [CrossRef]
21. Liang, S.; Yoshihira, T.; Sato, C. Grain yield responses to planting density in twin and narrow row cultivation of early cultivars in maize. *Grassl. Sci.* **2020**, *66*, 183–193. [CrossRef]
22. Van Roekel, R.J.; Coulter, J.A. Agronomic responses of corn hybrids to row width and plant density. *Agron. J.* **2012**, *104*, 612–620. [CrossRef]
23. Farnham, D.E. Row spacing, plant density, and hybrid effects on corn grain yield and moisture. *Agron. J.* **2001**, *93*, 1049–1053. [CrossRef]
24. Ramezani, M.; Abandani, R.R.S.; Mobasser, H.R.; Amiri, E. Effects of row spacing and plant density on silage yield of corn (*Zea mays* L. cv. sc704) in two plant patterns in North of Iran. *Afr. J. Agr. Res.* **2011**, *6*, 1128–1133.
25. Zhang, Y.Q.; Yang, H.S.; Li, C.F.; Zhao, M.; Luo, F.; Zhang, R.F. Effects of strip-till with staggered planting on yield formation and shoot-root characteristics of spring maize in irrigation area of Xiliaohe plain. *Acta Agron. Sin.* **2020**, *46*, 902–913.
26. Hou, P.; Liu, Y.; Liu, W.M.; Liu, G.Z.; Xie, R.Z.; Wang, K.R.; Ming, B.; Wang, Y.H.; Zhao, R.L.; Zhang, W.J.; et al. How to increase maize production without extra nitrogen input. *Resour. Conserv. Recycl.* **2020**, *160*, 104913. [CrossRef]
27. Chen, Y.Y.; Fan, P.S.; Mo, Z.W.; Kong, L.L.; Tian, H.; Duan, M.Y.; Li, L.; Wu, L.J.; Wang, Z.M.; Tang, X.R.; et al. Deep placement of nitrogen fertilizer affects grain yield, nitrogen recovery efficiency, and root characteristics in direct-seeded rice in South China. *J. Plant Growth Regul.* **2021**, *40*, 379–387. [CrossRef]
28. Liu, T.Q.; Li, S.H.; Guo, L.G.; Cao, C.G.; Li, C.F.; Zhai, Z.B.; Zhou, J.Y.; Mei, Y.M.; Ke, H.J. Advantages of nitrogen fertilizer deep placement in greenhouse gas emissions and net ecosystem economic benefits from no-tillage paddy fields. *J. Clean. Prod.* **2020**, *263*, 121322. [CrossRef]
29. Xia, L.L.; Li, X.B.; Ma, Q.Q.; Lam, S.K.; Wolf, B.; Kiese, R.; Butterbach-Bahl, K.; Chen, D.L.; Li, Z.A.; Yan, X.Y. Simultaneous quantification of N_2, NH_3 and N_2O emissions from a flooded paddy field under different N fertilization regimes. *Glob. Chang. Biol.* **2020**, *26*, 2292–2303. [CrossRef]
30. Jiang, C.Q.; Ren, X.X.; Wang, H.Y.; Lu, D.J.; Zu, C.L.; Wang, S.J. Optimal nitrogen application rates of one-time root zone fertilization and the effect of reducing nitrogen application on summer maize. *Sustainability* **2019**, *11*, 2979. [CrossRef]
31. Xu, J.Z.; Liao, L.X.; Tan, J.Y.; Shao, X.H. Ammonia volatilization in gemmiparous and early seedling stages from direct seeding rice fields with different nitrogen management strategies: A pots experiment. *Soil Tillage Res.* **2013**, *126*, 169–176. [CrossRef]
32. Zhao, X.H.; Yu, H.Q.; Wen, J.; Wang, X.G.; DU, Q.; Wang, J.; Wang, Q. Response of root morphology, physiology and endogenous hormones in maize (*Zea mays* L.) to potassium deficiency. *J. Integr. Agric.* **2016**, *15*, 785–794. [CrossRef]
33. Wu, P.; Chen, G.Z.; Liu, F.; Cai, T.; Zhang, P.; Jia, Z.K. How does deep-band fertilizer placement reduce N_2O emissions and increase maize yields? *Agr. Ecosyst. Environ.* **2021**, *322*, 107672. [CrossRef]
34. Wu, P.; Liu, F.; Li, H.; Cai, T.; Zhang, P.; Jia, Z.K. Suitable fertilizer application depth can increase nitrogen use efficiency and maize yield by reducing gaseous nitrogen losses. *Sci. Total Environ.* **2021**, *781*, 146787. [CrossRef]
35. Guo, L.; Ning, T.; Nie, L.; Li, Z.; La, R. Interaction of deep placed controlled-release urea and water retention agent on nitrogen and water use and maize yield. *Eur. J.* **2016**, *75*, 118–129. [CrossRef]
36. Department of Agriculture and Rural Affairs of Jilin Province. *The Agricultural Main Promotion Varieties and Technologies in Jilin Province in 2019 According to Jilin Provincial Department of Agriculture*; Department of Agriculture: Jilin, China, 2019.
37. Ren, H.; Qi, H.; Zhao, M.; Zhou, W.B.; Wang, X.B.; Gong, X.W.; Jiang, Y.; Li, C.F. Characterization of source-sink traits and carbon translocation in maize hybrids under high plant density. *Agronomy* **2022**, *12*, 961. [CrossRef]

38. Wang, Y.J.; Lv, Y.J.; Liu, H.T.; Bian, S.F.; Wang, L.C. Integrated management of high-yielding and high nutrient efficient spring maize in Northeast China. *Sci. Agric. Sin.* **2019**, *52*, 3533–3535.
39. Lv, Y.J.; Wang, Y.J.; Wang, L.C.; Zhu, P. Straw return with reduced nitrogen fertilizer maintained maize high yield in Northeast China. *Agronomy* **2019**, *9*, 229. [CrossRef]
40. Ritchie, S.W.; Hanway, J.J.; Benson, G.O. *How a Corn Plant Develops*; Special Report No. 48; Iowa State University of Science and Technology Cooperative Extension Service: Ames, IA, USA, 1993; Volume 48, p. 21.
41. Piao, L.; Li, M.; Xiao, J.L.; Gu, W.R.; Zhan, M.; Cao, C.G.; Zhao, M.; Li, C.F. Effects of soil tillage and canopy optimization on grain yield, root growth, and water use efficiency of rainfed maize in Northeast China. *Agronomy* **2019**, *9*, 336. [CrossRef]
42. Ren, B.Z.; Li, X.; Dong, S.T.; Liu, P.; Zhao, B.; Zhang, J.W. Soil physical properties and maize root growth under different tillage systems in the North China Plain. *Crop J.* **2018**, *6*, 669–676. [CrossRef]
43. Wang, X.B.; Zhou, B.Y.; Sun, X.F.; Yue, Y.; Ma, W.; Zhao, M. Soil tillage management affects maize grain yield by regulating spatial distribution coordination of roots, soil moisture and nitrogen status. *PLoS ONE* **2015**, *10*, e0129231. [CrossRef] [PubMed]
44. Ku, L.X.; Zhao, W.M.; Zhang, J.; Wu, L.C.; Wang, C.L.; Wang, P.A.; Zhang, W.Q.; Chen, Y.H. Quantitative trait loci mapping of leaf angle and leaf orientation value in maize (*Zea mays* L.). *Theor. Appl. Genet.* **2010**, *121*, 951–959. [CrossRef]
45. You, D.B.; Tian, P.; Sui, P.X.; Zhang, W.K.; Yang, B.; Qi, H. Short-term effects of tillage and residue on spring maize yield through regulating root-shoot ratio in Northeast China. *Sci. Rep.* **2017**, *7*, 13314. [CrossRef]
46. Tian, P.; Lian, H.L.; Wang, Z.Y.; Jiang, Y.; Li, C.F.; Sui, P.X.; Qi, H. Effects of deep and shallow tillage with straw incorporation on soil organic carbon, total nitrogen and enzyme activities in Northeast China. *Sustainability* **2020**, *12*, 8679. [CrossRef]
47. Olsen, S.; Sommers, L.; Page, A. *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties of Phosphorus*; American Society of Agronomy: Madison, WI, USA, 1982; Volume 9, pp. 403–430.
48. Mulumba, L.N.; Lal, R. Mulching effects on selected soil physical properties. *Soil Tillage Res.* **2008**, *98*, 106–111. [CrossRef]
49. Jin, L.B.; Cui, H.Y.; Li, B.; Zhang, J.W.; Dong, S.T.; Liu, P. Effects of integrated agronomic management practices on yield and nitrogen efficiency of summer maize in North China. *Field Crop. Res.* **2012**, *134*, 30–35. [CrossRef]
50. Liu, T.; Song, F.; Liu, S.; Zhu, X. Canopy structure, light interception, and photosynthetic characteristics under different narrow-wide planting patterns in maize at silking stage. *Span. J. Agric. Res.* **2011**, *9*, 1249. [CrossRef]
51. Liu, Z.; Zhu, K.L.; Dong, S.T.; Liu, P.; Zhao, B.; Zhang, J.W. Effects of integrated agronomic practices management on root growth and development of summer maize. *Eur. J. Agron.* **2017**, *84*, 140–151. [CrossRef]
52. Gao, J.; Shi, J.; Dong, S.T.; Liu, P.; Zhao, B.; Zhang, J.W. Grain yield and root characteristics of summer maize (*Zea mays* L.) under shade stress conditions. *J. Agron. Crop Sci.* **2017**, *203*, 562–573. [CrossRef]
53. Gheysari, M.; Sadeghi, S.H.; Loescher, H.W.; Amiri, S.; Zareian, M.J.; Majidi, M.M.; Asgarinia, P.; Payero, J.O. Comparison of deficit irrigation management strategies on root, plant growth and biomass productivity of silage maize. *Agr. Water Manag.* **2017**, *182*, 126–138. [CrossRef]
54. Feng, G.Z.; He, X.L.; Coulter, J.A.; Chen, Y.L.; Gao, Q.; Mi, G.H. Effect of limiting vertical root growth on maize yield and nitrate migration in clay and sandy soils in Northeast China. *Soil Tillage Res.* **2019**, *195*, 104407. [CrossRef]
55. York, L.M.; Galindo-Castañeda, T.; Schussler, J.R.; Lynch, J.P. Evolution of US maize (*Zea mays* L.) root architectural and anatomical phenes over the past 100 years corresponds to increased tolerance of nitrogen stress. *J. Exp. Bot.* **2015**, *66*, 2347–2358. [CrossRef]
56. Guan, D.H.; Al-Kaisi, M.M.; Zhang, Y.S.; Duan, L.S.; Tan, W.M.; Zhang, M.C.; Li, Z.; Li, Z.H. Tillage practices affect biomass and grain yield through regulating root growth, root-bleeding sap and nutrients uptake in summer maize. *Field Crop Res.* **2014**, *157*, 89–97. [CrossRef]
57. Ahmed, S.; Shima, B.; Yasmin, N.; Mohammad, A.; Alam, S.; Islam, M.R. Effects of row distance and nitrogen rate on canopy efficiency and yield of maize. *Int. J. Biol. Sci.* **2018**, *12*, 126–135.
58. Battaglia, M.; Lee, C.; Thomason, W.; Van Mullekom, J. Effects of corn row width and defoliation timing and intensity on canopy light interception. *Crop Sci.* **2019**, *59*, 1718–1731. [CrossRef]
59. Setter, T.L.; Flannigan, B.A.; Melkonian, J. Loss of kernel set due to water deficit and shade in maize: Carbohydrate supplies, abscisic acid, and cytokinins. *Crop Sci.* **2001**, *41*, 1530–1540. [CrossRef]
60. Wang, Y.S.; Janz, B.; Engedal, T.; Neergaard, A.D. Effect of irrigation regimes and nitrogen rates on water use efficiency and nitrogen uptake in maize. *Agr. Water Manag.* **2017**, *179*, 271–276. [CrossRef]