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Subsoiling Improves the Photosynthetic Characteristics of Leaves and Water Use Efficiency of Rainfed Summer Maize in the Southern Huang-Huai-Hai Plain of China

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Abstract: In the southern Huang-Huai-Hai (HHH) region, China, maize production is frequently threatened by waterlogging at the seedling stage and by drought at the big flare stage. A two-year field experiment was performed to explore whether subsoiling (SS) in the winter wheat season could improve the photosynthetic capacity and increase the water use efficiency (WUE) of summer maize using the variety, *Luyu9105*. A split design was adopted in the experiment. The main plots used tillage practices, including SS and rotary tillage (RT). The subplots consisted of two irrigation methods, i.e., applied supplemental irrigation at the big flare stage (I) and no irrigation at the big flare stage (NI). The results showed that the SS treatment significantly increased soil water content (SWC) in the 40–60 cm soil layer. The SS treatment improved green leaf area index (gLAI) by 15.1%–30.2%, and enhanced the ear-leaf net photosynthetic rate (P_n), stomatal conductance (g_s), intercellular CO_2 concentration (c_i) and transpiration rate (T_r), and was accompanied by an increase in the grain-filling duration (T) by 5 days and the mean grain-filling rate (V_a). The SS treatment decreased the stomatal limitation (L_s), indicating that RT treatment, which was under lower SWC, led to a decrease in P_n. Applied supplemental irrigation under RT treatment was able to compensate for the growth of leaves, but could not reverse the decreasing trend in the gLAI. Ultimately, the SS treatment improved WUE by 9.1%–9.9%, and increased grain yields by 10.0%–29.3%. Therefore, this study showed that in the southern Huang-Huai-Hai Plain, which has a yellow cinnamon soil type, the practice of SS can improve the photosynthetic characteristics of leaves and WUE of rainfed summer maize.

Keywords: *Zea mays* L.; subsoiling; green leaf area index; dry matter accumulation; water use efficiency; grain yield

1. Introduction

The Huang-Huai-Hai (HHH) farming region is one of the most important maize-producing regions in China, accounting for 35.3% of China's total maize yield from 1995 to 2007 [1–3]. Anhui Province is located in the southern HHH Plain. Shallow rotary tillage (RT) before the sowing of winter wheat and no-tillage of summer maize constitute the main cropping practices in this region [1,4,5]. However, the agricultural production in Anhui Province is mainly rainfed, and changes in the climate and variation in the annual and seasonal distribution of precipitation have affected water resources; this is threatening summer maize production [5–7].

Previous studies have shown that no-tillage or reduced-tillage practices are important climate-minded, conservation agriculture practices [8,9] and these methods have been promoted over the past few decades as sustainable farming practices that enhance the adaptive capacity of maize production under drought and heat stress [10]. In the semi-arid north China Plain, eleven years of no tillage has enhanced the mean percentage of macroaggregates and the macroporosity, particularly in dry years, and increased the soil organic matter and available nutrients in the top 10 cm soil layer [11]. However, in the southern HHH Plain which is characterized by yellow cinnamon soil, the uneven distribution of rainfall and no tillage in the long term may have adverse effects, including increased soil bulk density (SBD) in the top 10–20 cm soil layer and a reduction in the air-filled pore space, which prevents the infiltration and storage of water and aggravates water stress [1,3,12–14] especially in very wet seasons, which results in a decrease in the grain yield [10]. Moreover, topsoil is usually too loose to retain soil moisture under RT [15,16]. Under such conditions, one approach to achieve improved maize production is to minimize abiotic stress by adopting a proper soil tillage strategy such as subsoiling (SS) for winter wheat-summer maize double-cropping systems to improve the soil water content (SWC).

Subsoiling is an important strategy to break up the hardpan layer and reduce the SBD without turning over the infertile subsoil at the top [17–19]. In addition, by improving the soil structure, and establishing ideal conditions for root development and maintaining root activity, the practice of SS can effectively improve the water and nutrient supply to the aboveground portions of plants during grain filling [4]. This effectively delays plant senescence [20,21], and thereby increases yields and the water use efficiency (WUE) [22]. Sun [4] pointed out that SS tillage increased green leaf area index (gLAI), ear-leaf net photosynthetic rate ($P_{n)}$ and the chlorophyll fluorescence characteristics by enhancing dry matter accumulation (DMA) at the post-silking stage. Wang [18] found that SS improved both root DMA and shoot DMA at the post-silking stage and increased the maximum and mean grain-filling rate (V_a), thus increasing the grain yield.

However, previous studies have mainly focused on the effects of SS on the soil properties [23], and have been mainly located in the semi-arid North China Plain. Little is known about how SS tillage affects maize growth, especially in a rainfed area with an ample but uneven distribution of precipitation. Our study aims to clarify whether SS in the winter wheat season could improve the photosynthetic capacity of summer maize and increase WUE, thereby increasing the grain yield. In this context, we conducted this study with the objective of assessing SS practices in the winter wheat season in terms of its impact on (1) gLAI, photosynthetic capacity and chlorophyll fluorescence of leaves; (2) aboveground DMA and dry matter translocation (DMT); and (3) grain-filling, grain yield, yield components and WUE in the summer maize season.

2. Materials and Methods

2.1. Plant Materials and Culture Conditions

A field experiment was conducted at the experimental station of the Anhui Academy of Agricultural Sciences, China (31°57′ N, 117°11′ E), in 2016 and 2017. The region has a temperate continental monsoon climate. The annual mean temperature over the last 30 years is 15.7 °C, and the mean annual precipitation is 1000 mm. The monthly distribution of precipitation, the annual total precipitation and mean temperature in 2016 and 2017 at the experimental site are shown in Table 1. The soil is yellow cinnamon with a pH value of 5.6, and the nutrient conditions of the soil in the top 20 cm in 2016 are shown in Table 2. The soil available P was extracted with 0.5 mol/L $NaHCO_3$, and the available K was extracted with 1 mol/L $C_2H_7NO_2$, by using the Mo-Sb anti-spectrophotometer method and the flame photometry method. The SBD was measured prior to sowing using the cutting-ring method, the values for SBD and SWC in 2016 and 2017 at the beginning of the summer maize season are provided in Table 3.

Table 1. The monthly distribution of precipitation and mean temperature in 2016 and 2017.

Month	2016 Total Precipitation (mm)	2016 Mean Temperature (°C)	2017 Total Precipitation (mm)	2017 Mean Temperature (°C)
January	49.4	3.4	60.9	5.4
February	17.6	6.7	40.6	6.4
March	57.4	11.9	68.4	10.8
April	139.4	18.0	64.2	18.0
May	125	20.7	123.6	23.1
June	191	24.6	49.9	25.7
July	295	28.8	63.5	30.8
August	60.4	29.4	243.2	28.1
September	129	24.4	111.6	23.2
October	268.1	17.8	97.5	16.4
November	96	11.2	10.8	16.4
December	73.7	7.0	13.6	11.8
Amount during June and September	675.4	–	468.2	–
Total amount	1502	–	947.8	–

"–"Means there was no date.

Table 2. The nutrient conditions of the top 20 cm soil layer in 2016.

Soil Nutrient	Content
Organic matter (g kg^{-1})	21.6
Hydrolysable N (mg kg^{-1})	118.4
Available phosphorus (mg kg^{-1})	25.4
Available K (mg kg^{-1})	269.6

Table 3. Soil bulk density and soil water content in 2016 and 2017.

			Soil Depth (cm) 0–10	10–20	20–30	30–40	40–50	50–60
2016	SS	SBD (g cm^{-3})	1.47 c	1.49 bc	1.57 ab	1.62 a	1.55 ab	1.51 b
		SWC (%)	19.27 b	19.86 b	20.24 ab	21.69 a	22.80 a	23.61 a
	RT	SBD (g cm^{-3})	1.57 a	1.64 b	1.58 a	1.56 a	1.56 a	1.57 a
		SWC (%)	19.69 a	19.47 a	20.10 a	21.45 a	21.56 a	22.30 a
2017	SS	SBD (g cm^{-3})	1.46 c	1.49 bc	1.52 ab	1.58 a	1.51 ab	1.49 b
		SWC (%)	14.52 b	15.36 b	16.75 a	17.42 a	17.96 a	18.29 a
	RT	SBD (g cm^{-3})	1.59 a	1.62 a	1.61 a	1.58 a	1.57 a	1.57 a
		SWC (%)	14.53 a	15.21 a	15.89 a	16.74 a	16.87 a	17.02 a

Values followed by different letters are significantly different in terms of soil bulk density (SBD) and soil water content (SWC) of different tillage practices.

2.2. Experimental Design

The experiment involved a two-factor split-plot design. The soil tillage practice was the main plot factor, and irrigation at the big flare stage was the subplot factor. The two tillage practices were SS tillage (40 cm deep) and RT (15 cm deep), which were applied in the winter wheat season. In the summer maize season, each tillage practice comprised two irrigation patterns: supplemental irrigation applied at the big flare stage (I) and no supplemental irrigation at the big flare stage (rainfed) (NI). The four treatments were SS + I, RT + I, SS + NI and RT + NI, with four replicates. The length and width of each plot was 12 m × 12 m, each plot being 144 m^2.

The winter wheat variety was *Annong 0711*, and the summer maize cultivar *Luyu9105* were chosen for this study, as it is widely grown in Anhui Province and is high-yielding, multi-resistant and highly adaptable. After the maize and wheat were harvested, the straw was chopped into small pieces at lengths of less than 10 cm and returned to the soil of the experimental plots using a combine harvester. In the winter wheat season, the size of each plot was also 12 m × 12 m, the row spacing was 20 cm, and there was no supplemental irrigation in the winter wheat season. The maize was sown manually using a seed planting machine at a planting density of 75,000 plants ha^{-1} with a row spacing of 60 cm. The planting dates were June 25, 2016 and June 18, 2017, and the harvesting dates were October 18, 2016, and October 8, 2017. The N fertilizer was urea (N 46%) and compound fertilizer (NPK 15:15:15), and the application rate in winter wheat and summer maize was 240 kg ha^{-1}, respectively. The application rate of P and K fertilizer were 105 kg ha^{-1} and 135 kg ha^{-1}, respectively, using the compound fertilizer. Due to insufficient K fertilizer, we applied K_2SO_4 as a supplement. All the fertilizer was applied per plot prior to sowing. Weeds, disease, and insect pests were rigorously controlled.

At the big flare stage (11–12 visible leaves, on July 25 in 2016 and July 18 in 2017) of summer maize, 300 m^3 ha^{-1} of supplemental irrigation was applied, and a sprinkler system was used for all the irrigation treatments. The gap between the two adjacent SS and RT treatment plots was 1.5 m to avoid the interference of supplemental irrigation. No further irrigation during maize growth was used in any of the treatments.

2.3. gLAI

The leaves were grouped into three leaf layers, i.e., ear leaves (three-ear leaves), above-ear leaves (the leaves above the three-ear leaves), and below-ear leaves (the leaves below the three-ear leaves). At the big flare stage and silking stage, three plants were randomly selected per plot to determine the gLAI [24]. The gLAI was calculated as follows:

$$\mathrm{gLAI} = \Sigma\ (\mathrm{A} \times \mathrm{B} \times 0.75) \times \mathrm{C}\ /\ \mathrm{D} \quad (1)$$

where A is the leaf length, B is the maximum leaf width, C is the plant density, and D is the planted soil area.

2.4. Leaf Gas Exchange Characteristics

At the big flare (July 25 in 2016, July 18 in 2017), silking (August 10 in 2016, August 5 in 2017) and mid-filling (Autumn 30 in 2016, Autumn 28 in 2017) stages, the P_n, stomatal conductance (g_s), intercellular CO_2 concentration (c_i) and transpiration rate (T_r) of the ear leaves were measured using a portable gas exchange system (LI-6400, LI-COR, Lincoln, USA), and the stomatal limitation (L_s) was calculated. Six plants from each plot were measured on clear days from 9:30–11:00 a.m. Consistent measurement conditions were used: an LED light source, a photosynthetically active radiation (PAR) value of 1400 μmol m^{-2} s^{-1}, a flow rate of 500 cm^3 min^{-1}, a constant CO_2 concentration of 400 μmol mol^{-1}, an air temperature of 30 °C, and a relative humidity of 65% [25].

The chlorophyll fluorescence was determined for the ear leaves by nondestructively measuring the photophysiological parameters using pulse amplitude modulation fluorometry (PAM-2500, Walz, Germany) at the big flare and silking stages. The initial fluorescence (F_o) and maximal fluorescence (F_m) were measured after 30 min of dark adaptation. The maximal PSII photochemical efficiency (F_v/F_m), the potential PSII photochemical efficiency (F_v/F_o), effective quantum yield of PSII (Φ_{PSII}) and photochemical fluorescence quenching coefficients (qP) were also recorded.

2.5. DMA and DMT

In the middle of each plot, three adjacent plants were manually cut at ground level at the silking and maturity stages in the three replicates. Fresh dry matter samples were heated in an oven for 30 min at 105 °C to deactivate the enzymes and were then dried at 80 °C to a constant weight to measure their DMA. The DMT from the vegetative organs to the grain between silking and maturity, the DMA at the post-silking stage and the contribution of dry matter at the post-silking stage to the grain weight (CDMGW) were calculated following the methods of Wu et al. [5].

$$\text{DMT} = \text{DMA at the silking stage - DMA at the maturity stage} \tag{2}$$

$$\text{The DMA at the post-silking stage} = \text{Grain weight at maturity stage} - \text{DMT} \tag{3}$$

$$\text{CDMGW} = \frac{\text{DMA at the post} - \text{silking stage}}{\text{Grain yield}} \times 100 \tag{4}$$

2.6. Grain-Filling Characteristics

The silking date was recorded when the silks emerged in 50% of the plants in a plot. Four ears in each plot were randomly selected. The plants were harvested at 11, 18, 26, 34, 40, 43, 46, and 49 days after silking, and 100 grains were cut and removed from the middle of each sampled ear [26]. The dry weight of 100 grains for each ear was measured after drying to a constant weight in a forced-air oven at 80 °C.

The dynamics of grain weight during grain filling followed the Richards growth equation [25,27]:

$$\text{Y} = \frac{K}{1 + e^{A+Bt}} \tag{5}$$

where Y is the grain weight, K is the ultimate grain weight, t is the day after pollination, and A and B are the coefficients determined by the regression. The early grain-filling period (t_1), the middle grain-filling period (t_2), the late grain-filling period (t_3), the duration of the early grain-filling period (T_1), the duration of the middle grain-filling period (T_2), the duration of the late grain-filling period (T_3), the grain-filling duration (T), the mean grain-filling rate (V_a), the maximum grain-filling rate (V_m), the grain weight during the early grain-filling period (W_1), the grain weight during the middle grain-filling period (W_2), the grain weight during the late grain-filling period (W_3), the grain-filling rate during the early grain-filling period (V_1), the grain-filling rate during the middle grain-filling period (V_2) and the grain-filling rate during the late grain-filling period (V_3) were calculated using the following equations:

$$\text{t}_1 = \frac{A - \ln(2 + 1.732)}{(-B)} \tag{6}$$

$$\text{t}_2 = \frac{A + \ln(2 + 1.732)}{(-B)} \tag{7}$$

$$\text{t}_3 = \frac{-(4.59512 + \text{A})}{B} \tag{8}$$

$$\text{T}_1 = \text{t}_1 \tag{9}$$

$$\text{T}_2 = \text{t}_2 - \text{t}_1 \tag{10}$$

$$\text{T}_3 = \text{t}_3 - \text{t}_2 \tag{11}$$

$$\text{T} = \text{t}_3 \tag{12}$$

$$\text{V}_\text{a} = \text{K} / \text{t}_3 \tag{13}$$

$$\text{V}_\text{m} = (\text{-B} \times \text{K}) / 4 \tag{14}$$

$$\text{W}_1 = \frac{K}{1 + e^{A+Bt_1}} \tag{15}$$

$$\text{W}_2 = \frac{K}{1 + e^{A+Bt_2}} - \frac{K}{1 + e^{A+Bt_1}} \tag{16}$$

$$W_3 = \frac{K}{1+e^{A+Bt_3}} - \frac{K}{1+e^{A+Bt_1}} \tag{17}$$

$$V_1 = W_1 / T_1 \tag{18}$$

$$V_2 = W_2 / T_2 \tag{19}$$

$$V_3 = W_3 / T_3 \tag{20}$$

2.7. Grain Yield

At the maturity stage, 30 ears were harvested from three rows (12 m^2) at the center of each plot to determine the yield and ear characteristics, including the row number, and kernel number per row. All the kernels were air-dried, and grain yield was calculated at 14% moisture, which is the standard for maize storage or sale in China (GB/T29890-2013). The grain yield was calculated as follows [25]:

$$\text{The grain yield(kg ha}^{-1}) = A \times B \times C \times (1-14\%) / 10^6 \times (1\text{-}D) \tag{21}$$

where A is the harvested ears (ears ha^{-1}); B is the kernel number per ear; C is the 1000-grain weight (g 1000 $grains^{-1}$); D is the sample moisture content (%).

2.8. SWC and WUE

The SWC was measured by the oven-drying method. Soil samples were collected manually using a soil auger (with a 5 cm diameter) at 10 cm increments to a depth of 40 cm in 2016 and 20 cm increments to a depth of 60 cm in 2017 in all experimental plots to measure the SWC. Measurements were performed before irrigation at the big flare stage and the harvest season of summer maize. SWC was defined as follows [28]:

$$\text{SWC} = \frac{W_{fresh} - W_{dry}}{W_{dry}} \times 100 \tag{22}$$

where W_{fresh} and W_{dry} are soil fresh weight and soil dry weight, respectively.

The seasonal maize evapotranspiration (ET_a) (mm) and WUE (kg ha^{-1} mm^{-1}) were calculated according to Wang et al. [29].

$$\text{ETa} = P + I + C_r - R - D \pm \Delta S \tag{23}$$

$$\text{WUE} = Y / \text{ETa} \tag{24}$$

where P is the seasonal total precipitation (mm), I is the seasonal irrigation (mm), C_r is the seasonal upward capillary flow into the root zone (mm), R is the seasonal runoff (mm), and D is the downward flux below the crop root zone. The C_r, R, and D were considered to be zero because the surface runoff was nonexistent, and there was negligible capillary rise from 20–30 m below the soil surface during the growing season. The seasonal change in the soil water storage at 0–100 cm is ΔS, and Y is the maize grain yield (kg ha^{-1}).

2.9. Statistical Analysis

Data were analyzed by analysis of variance (ANOVA) at the 5% significance level to determine the differences between the different treatments using SPSS 13.0 (SPSS, Chicago, IL, USA). The differences were determined by least significant difference (LSD) multiple-range tests at the 5% significance level. All of the figures were drawn using SigmaPlot 10.0 (Sigmaplot, California, CA, USA).

3. Results

3.1. gLAI

The SS treatment significantly improved the gLAI by 15.1 and 17.5% in 2016, and 30.2 and 17.5% in 2017, compared to the RT treatment (Figure 1). The RT + I treatment increased the gLAI values by 19.7% and 17.3% at the silking stage in 2016 and 2017, respectively, compared with the RT + NI treatment (Figure 1). The SS + I treatment significantly increased the gLAI values by 19.6% and 17.4% in 2016 and by 43.3% and 38.0% in 2017, compared to RT + I and RT + NI treatments, respectively (Figure 1). However, there was no significant difference between the SS + NI and RT + I treatments.

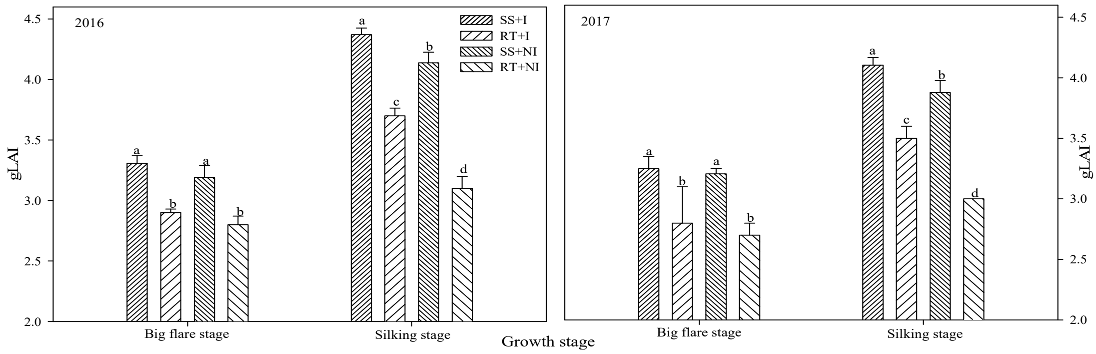

Figure 1. Effects of different tillage practices on the green leaf area index (gLAI) in maize. Different small letters in the same growing stage indicate significant differences between tillage practices.

At the silking stage, the gLAI values at the different leaf layers were ranked as follows: below-ear leaves > ear leaves > above-ear leaves (Figure 2). The gLAI values in the SS treatment were significantly increased by 11.1% in the above-ear leaves, 30.2% in the ear leaves, and 36.8% in the below-ear leaves in 2016 and by 22.7%, 17.5%, and 17.5%in 2017, compared to those under the RT treatment. The RT + I treatment significantly increased gLAI in 2016 and 2017, by 8.4% and 25.6% in the above-ear leaves, 9.5% and 13.6% in the ear leaves, and 39.8% and 14.8% in the below-ear leaves, respectively, compared to those in the RT + NI treatment. In addition, compared with the RT + I treatment, the SS + NI treatment significantly improved the gLAI values of the ear leaves and below-ear leaves, although there was no significant difference in the above-ear leaves.

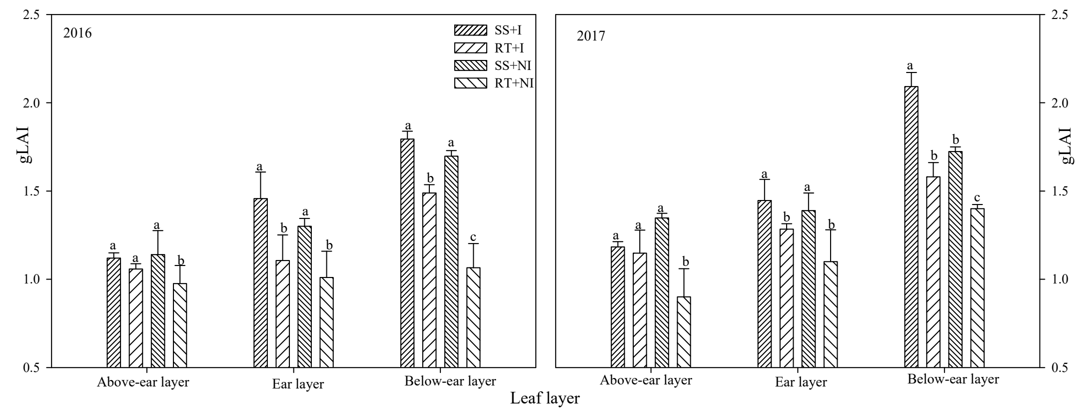

Figure 2. Effects of different tillage practices on the gLAI of different leaf layers in maize. Different small letters under the same leaf layer indicate significant differences between tillage practices.

3.2. *Leaf Photosynthetic Capacity*

In the growing season, the P_n values were ranked as follows: SS + I > RT + I > SS + NI > RT + NI (Table 4). The SS treatment led to a significant increase in P_n by 4.4%, 15.6%, and 18.6% in 2016 and by 4.8%, 11.5%, and 18.8% in 2017 at the big flare stage, silking stage and mid-filling stage, respectively. Increases in g_s, c_i and T_r were observed in the SS treatment, while, L_s was decreased by 7.5 and 13.3% in 2017 at the big flare and mid-filling stage, respectively. The RT + I treatment significantly increased P_n by 2.0, 7.9 and 9.0% at different stages, respectively, compared to the RT + NI treatment, and this was accompanied by a decrease in g_s, c_i and T_r values and a decrease in L_s.

Table 4. Effects of different tillage practices on the photosynthetic capacity of summer maize at different growth stages.

Growth Stage	Treatment	2016					2017				
		P_n μmol m^{-2} s^{-1}	g_s mmol m^{-2} s^{-1}	c_i μmol mol^{-1}	T_r mmol m^{-2} s^{-1}	L_s	P_n μmol m^{-2} s^{-1}	g_s mmol m^{-2} s^{-1}	c_i μmol mol^{-1}	T_r mmol m^{-2} s^{-1}	L_s
Big Flare Stage	SS + I	29.7 ± 2.1 a	169.4 ± 25.9 b	69.0 ± 15.4 c	6.6 ± 0.8 a	82.7	35.4 ± 1.6 a	258.1 ± 30.4 a	109.3 ± 18.3 a	8.8 ± 0.7 a	72.7
	RT + I	27.7 ± 1.3 ab	168.6 ± 30.8 b	112.4 ± 16.0 b	5.4 ± 0.4 b	71.9	33.5 ± 2.3 ab	214.2 ± 43.8 b	83.5 ± 22.1 b	7.0 ± 1.0 ab	79.1
	SS + NI	27.2 ± 1.8 ab	144.7 ± 35.4 c	157.0 ± 21.0 c	5.6 ± 0.4 b	60.7	34.2 ± 1.9 a	244.7 ± 24.9 a	112.2 ± 33.7 a	5.6 ± 0.4 b	72.0
	RT + NI	26.8 ± 1.4 b	210.9 ± 36.8 a	153.4 ± 16.8 a	7.0 ± 0.7 a	61.6	32.9 ± 2.6 b	199.0 ± 28.0 b	91.3 ± 16.2 b	6.6 ± 0.6 b	77.2
Silking Stage	SS + I	36.5 ± 2.6 a	398.1 ± 21.3 a	179.2 ± 23.1 a	5.5 ± 0.1 a	55.2	32.1 ± 2.6 a	327.0 ± 26.7 a	171.2 ± 4.2 a	4.8 ± 0.2 a	57.2
	RT + I	30.5 ± 3.0 b	281.1 ± 25.4 b	172.3 ± 25.4 a	3.8 ± 0.2 b	56.9	27.8 ± 1.2 b	251.8 ± 11.4 b	171.0 ± 21.5 a	3.6 ± 0.1 a	57.2
	SS + NI	27.3 ± 1.5 bc	145.2 ± 29.4 d	142.1 ± 21.0 b	2.5 ± 0.1 b	64.5	27.7 ± 2.4 b	212.2 ± 38.7 c	158.1 ± 22.1 b	3.8 ± 0.7 a	60.5
	RT + NI	24.7 ± 2.7 c	204.8 ± 30.1 c	175.8 ± 23.8 a	3.2 ± 0.3 b	56.1	25.8 ± 1.8 b	208.1 ± 38.1 c	175.5 ± 12.4 a	3.1 ± 0.4 a	56.1
Mid-filling Stage	SS + I	31.7 ± 1.2 a	241.6 ± 26.5 a	144.4 ± 20.8 b	4.3 ± 0.4 a	63.9	33.4 ± 2.3 a	281.6 ± 26.1 a	241.8 ± 8.9 a	4.3 ± 0.4 b	39.5
	RT + I	24.0 ± 1.5 b	163.6 ± 24.1 b	153.0 ± 24.4 b	2.2 ± 0.1 b	61.7	26.9 ± 1.0 b	234.9 ± 26.5 b	195.2 ± 15.7 b	2.9 ± 0.3 b	51.2
	SS + NI	22.5 ± 1.1 b	281.6 ± 27.1 a	144.9 ± 23.4 a	4.1 ± 0.2 a	63.8	27.9 ± 1.3 b	239.0 ± 28.2 b	178.1 ± 21.3 c	6.3 ± 0.5 a	55.5
	RT + NI	21.7 ± 1.2 b	145.9 ± 22.5 b	142.1 ± 22.0 b	2.3 ± 0.3 b	64.5	24.7 ± 1.1 c	240.5 ± 31.2 b	166.4 ± 20.0 c	3.0 ± 0.5 b	58.4

Values followed by different letters are significantly different in terms of the photosynthetic characteristics of different tillage practices.

The SS treatment significantly improved the F_v/F_m and F_v/F_o (Figure 3), compared with the RT treatment. The SS treatment increased the Φ_{PSII} by 7.4% and 3.5% in 2016, and 2.4% and 1.5% in 2017, and increased qP by 7.0% in 2016, and 0.5% and 2.4% in 2017, respectively (Table 5). However, the application of supplemental irrigation at the big flare stage could alleviate the adverse effects on the F_v/F_m and F_v/F_o.

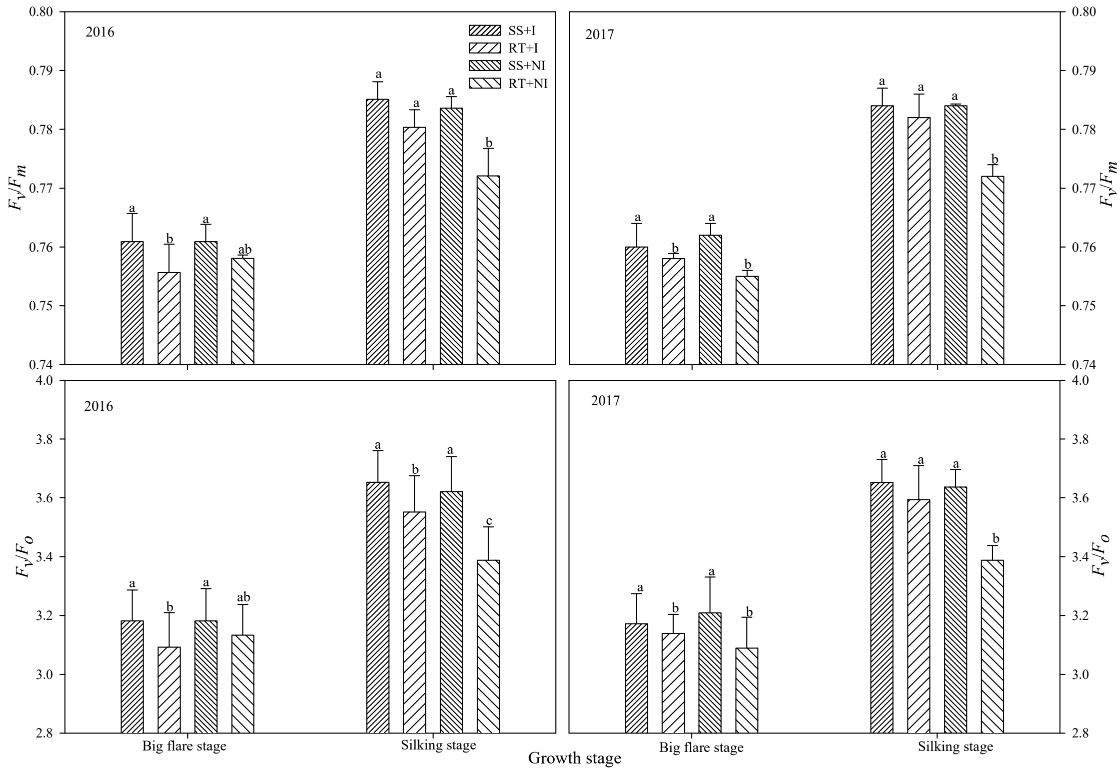

Figure 3. Effects of different tillage practices on the Fv/Fm and Fv/Fo of summer maize at different growth stages. Different small letters under the same growth stage indicate significant differences between tillage practices.

Table 5. Effects of different tillage practices on the Φ_{PSII} and qP of summer maize at different growth stages.

Growth Stage	Treatment	2016		2017	
		Φ_{PSII}	qP	Φ_{PSII}	qP
Big flare stage	SS + I	0.562 ± 0.006 a	0.81 ± 0.008 a	0.598 ± 0.008 a	0.824 ± 0.006 a
	RT + I	0.515 ± 0.008 b	0.772 ± 0.006 b	0.583 ± 0.034 a	0.881 ± 0.032 a
	SS + NI	0.573 ± 0.007 a	0.798 ± 0.006 a	0.589 ± 0.009 a	0.842 ± 0.015 a
	RT + NI	0.542 ± 0.010 c	0.731 ± 0.006 c	0.577 ± 0.015 a	0.808 ± 0.026 a
Silking stage	SS + I	0.620 ± 0.005 a	0.812 ± 0.010 ab	0.629 ± 0.005 a	0.882 ± 0.023 a
	RT + I	0.601 ± 0.008 ab	0.805 ± 0.009 ab	0.626 ± 0.005 ab	0.835 ± 0.016 ab
	SS + NI	0.615 ± 0.006 ab	0.803 ± 0.006 b	0.618 ± 0.001 ab	0.814 ± 0.006 ab
	RT + NI	0.592 ± 0.009 b	0.842 ± 0.018 a	0.614 ± 0.002 b	0.806 ± 0.005 b

Values followed by different letters are significantly different in terms of the Φ_{PSII} and qP of different tillage practices.

3.3. DMA and DMT

The DMA weight after the silking stage accounted for 54.0%–59.0% in 2016 and 56.2%–58.0% in 2017 (Figure 4). The SS treatment significantly increased the DMA at the silking and maturity stages by 9.8% and 8.2% in 2016, and by 8.4% and 10.5% in 2017, respectively. Compared with the RT + NI treatment, the RT + I treatment significantly increased DMA by 27.2% and 25.8% in 2016 and by 21.8%

and 12.0% in 2017, respectively. The SS + I treatment decreased the DMT and the contribution of DMT before the silking stage to the grain stage. The RT + NI treatment increased the DMT and the contribution of DMT before the silking stage to the grain stage (Table 6).

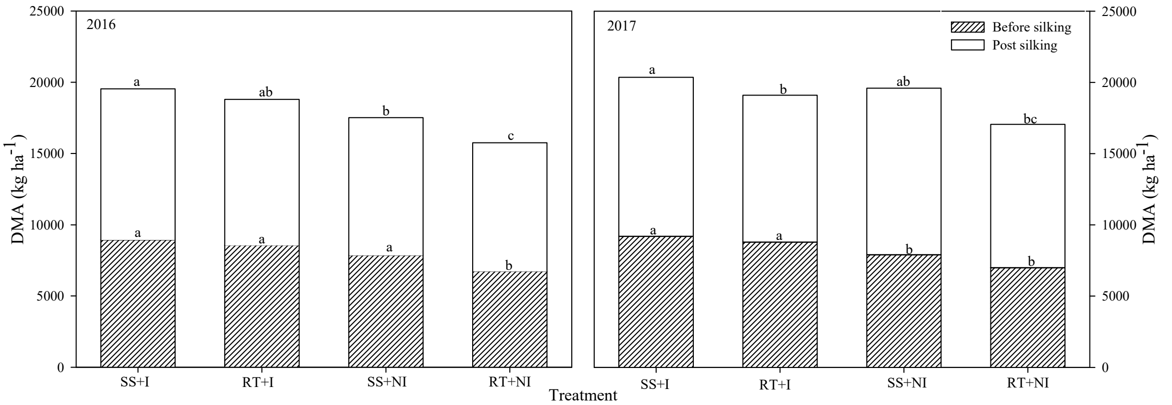

Figure 4. Aboveground dry matter accumulation (DMA)of different soil tillage practices. Different letters above the bars indicate significant differences between tillage practices.

Table 6. Dry matter translocation (DMT) from vegetative organs to grain and accumulation amount at the post silking stage.

Treatment	DMT before the Silking Stage (kg ha^{-1})	Contribution of DMT before the Silking Stage to Grain (%)	DMA at the Post Silking Stage (kg ha^{-1})	CDMGW (%)
		2016		
SS + I	1651.9	16.9	8147.2	83.1
RT + I	1664.6	17.3	7976.7	82.7
SS + NI	1807.0	18.8	7779.8	81.2
RT + NI	2290.2	26.1	6499.9	73.9
		2017		
SS + I	1784.8	16.8	8867.6	83.2
RT + I	2247.2	22.5	7746.4	77.5
SS + NI	3159.7	30.3	7256.3	69.7
RT + NI	2573.9	30.7	5822.4	69.3

3.4. Grain-Filling Characteristics

The SS treatment had a significant influence on the 100-grain weight, which was 10.4% higher than that in the RT treatment (Figure 5). The RT + I treatment significantly improved the 100-grain weight by 13.5%, compared to the RT + NI treatment, while there was no significant difference between the RT + I and SS + NI treatments.

The SS treatment improved the T, V_m and V_a (Table 7), while RT resulted in a decrease in K, T, V_a and V_m. Compared to the RT treatment, the SS treatment increased the T by 5 days, especially the duration of the middle (T_2) and late grain-filling periods (T_3) and the grain-filling rate of the early period (V_1). The results showed that SS can prolong the T and increase the V_a, which resulted in a significant increase in the grain weight.

3.5. Grain Yield and WUE

The SS treatment significantly increased grain yield by 9.0% in 2016 and 12.0% in 2017 (Table 8), compared with that of the RT treatment. The application of supplemental irrigation at the big flare stage effectively alleviated the reduction in grain yield induced by the RT treatment, which increased by 10.1% and 13.7% in 2016 and 2017, respectively, compared with that of the RT + NI treatment.

However, there was no significant difference between the SS + NI and RT + I treatments. The SS + I treatment enhanced grain yield by 6.9% and 17.7% in 2016 and by 13.7% and 29.3% in 2017, compared to the RT + I and RT + NI treatments. Moreover, the number of kernels per plant was higher in the SS treatments than in the RT treatment by 11.8% in 2016 and 11.0% in 2017.

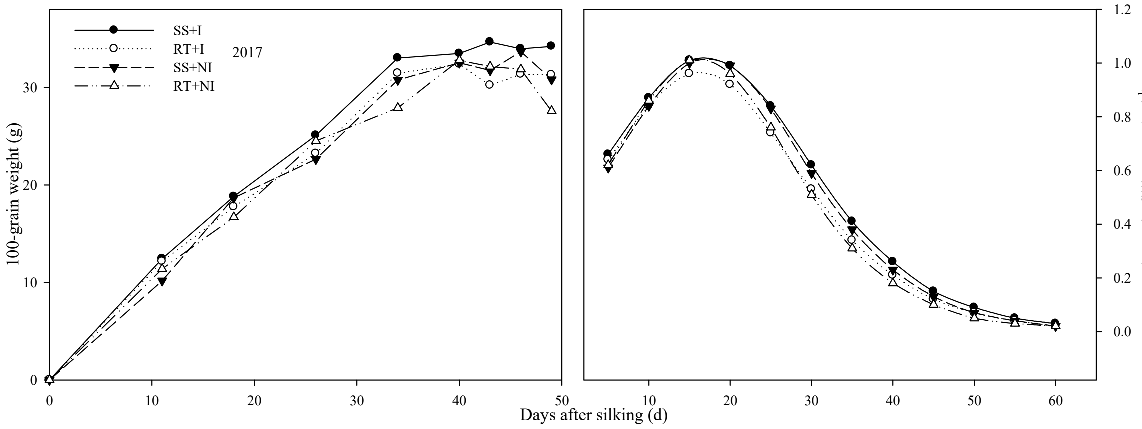

Figure 5. Effects of different tillage methods on grain weight accumulation and grain-filling rate.

Table 7. Effects of different tillage methods on grain-filling characteristic parameters.

Treatment	Simulative Equation	R^2	K	T_m	V_m	T	V_a	T_1	T_2	T_3	V_1	V_2	V_3
SS + I	$Y = 35.8164 / (1 + e^{(1.9395 - 0.114032x)})$	0.9884	35.62	17.01	1.02	57.31	0.63	5.46	23.10	28.75	1.39	0.90	0.51
RT + I	$Y = 32.7234 / (1 + e^{(1.9054 - 0.117603x)})$	0.9683	32.72	16.20	0.96	55.28	0.59	5.00	22.40	27.87	1.38	0.84	0.48
SS + NI	$Y = 33.4501 / (1 + e^{(2.1150 - 0.12783x)})$	0.9708	33.45	17.37	1.02	55.10	0.61	6.55	21.63	26.92	1.08	0.89	0.51
RT + NI	$Y = 31.7224 / (1 + e^{(2.0912 - 0.127825x)})$	0.9423	31.72	16.36	1.01	52.31	0.61	6.06	20.61	25.65	1.11	0.89	0.51
	CV (%)			2.88	3.01	2.13	3.49	5.29	2.14	2.14	7.21	3.01	3.01

Table 8. Effects of different tillage methods on grain yield.

Treatment	Yield (kg ha^{-1})	100-kernel Weight (g)	Kernels Per Year	Yield Increase Rate (%)	WUE (%)
		2016			
SS + I	9003.4 ± 264.0 a	38.0 ± 2.2 a	490.7 ± 9.2 a	17.7	14.0 ± 1.3 a
RT + I	8418.1 ± 243.1 a	37.9 ± 1.4 a	452.9 ± 5.3 b	10.1	13.0 ± 0.5ab
SS + NI	8509.2 ± 156.9 a	37. 9 ± 0.6 a	465.3 ± 3.8 b	11.2	13.7 ± 0.1 ab
RT + NI	7649.3 ± 189.4 b	37.1 ± 1.1 a	401.9 ± 2.9 c	–	12.4 ± 0.3 b
		2017			
SS + I	9520.0 ± 141.1 a	36.4 ± 1.0 a	465.8 ± 19.5 a	29.3	22.0 ± 0.3 a
RT + I	8370.0 ± 511.2 b	36.1 ± 1.5 a	421.5 ± 44.5 b	13.7	19.7 ± 0.4 b
SS + NI	8100.0 ± 365.0 bc	36.0 ± 0.8 a	443.4 ± 32.2 a	10.0	20.1 ± 0.9b
RT + NI	7363.3 ± 296.0 c	36.1 ± 0.5 a	397.3 ± 21.9 b	–	18.6 ± 0.6 b

Values followed by different small letters are significantly different at different tillage practices.

The SS treatment significantly increased the SWC by 5.4%, 4.9%, 9.3% and 9.0% in the 0–10 cm, 10–20 cm, 20–30 cm and 30–40 cm soil layers, respectively, in 2016. The SWC values increased by 4.3%, 3.8% and 11.5% in the 0–20 cm, 20–40 cm and 40–60 cm soil layers, respectively, in 2017 (Figure 6), compared to the RT treatment. The SS treatment significantly increased the WUE by 9.1% in 2016 and by 9.9% in 2017, compared to the RT treatment. With supplemental irrigation at the big flare stage, the RT + I treatment significantly increased the WUE by 4.8% in 2016 and 5.9% in 2017, compared to the RT + NI treatment. The SS + I treatment significantly increased the WUE by 2.2% in 2016 and 9.5% in 2017, compared to the SS + NI treatment (Table 8).

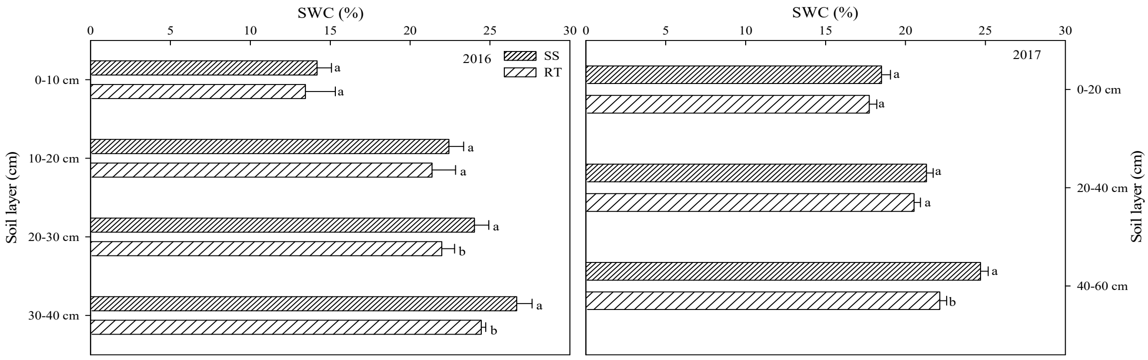

Figure 6. SWC in the 0–60 cm soil layer under different tillage practices at the big flare stage. Different small letters under the same soil layer indicate significant differences between tillage practices.

4. Discussion

4.1. Subsoiling Practice to Improve gLAI and Leaf Photosynthetic Function

Optimized tillage practices can alter the soil environment by facilitating both the physical and chemical characteristics of the soil, thereby improving the root function and increasing crop biomass [1,17]. The gLAI is an important indicator of canopy architecture at different growth stages, and a longer gLAI duration at the post-silking period is one of several morphophysiological traits associated with the improvement of maize yields [30]. However, until now, few studies have been conducted to determine how different leaf layers are affected by tillage practices. Our results indicated that SS treatment enhanced the gLAI. Supplemental irrigation applied under the RT treatment could compensate for the adverse effects of water deficiency on the gLAI, but the compensatory effect was still weaker than the effect of the SS + NI treatment. This finding illustrates that SS tillage could improve the storage of water in deeper soil and influence root growth and distribution in the soil [31]. The spatial distribution of the root system in a soil profile has a great influence on the absorption of soil water and nutrients [18,32,33]. In the experimental location, during June in 2016 and June 2017, the precipitation amount was 191 mm and 54 mm, respectively. However, from July 16 to August 2 in 2016, the total rainfall was only 22.5 mm, and from July 10 to August 1 in 2017, the total rainfall was only 7.9 mm, and this was accompanied by high temperatures, which may induce water and heat stress. The SS treatment decreased the soil bulk density of the deep soil layer and improved the SWC in the 30–40 cm soil layer, especially in 2016, under high precipitation at the seedling stage of the maize. In 2017, with lower precipitation at the silking stage, the SS practice enhanced the SWC in the 40–60 cm soil layer, which was necessary in the later growing season. With the improvement in deep SWC, the gLAI was improved, whereas long-term RT management caused soil compaction, the soil bulk density increased and water penetration was reduced [12–14]. Even when supplemental irrigation was applied at the big flare stage, a higher soil bulk density reduced water infiltration, which resulted in an increase in surface runoff; therefore, the soil water storage in the deep soil decreased. This resulted in an undesirable soil water environment for summer maize, especially for root growth [22,34,35], which may lead to abnormal growth of shoot parts [6,31] and decreased gLAI.

A higher gLAI can provide a larger source of photosynthate at the post-silking stage. Our study showed that SS caused a significant increase in P_n, g_s, c_i and T_r, accompanied by a significant decrease in L_s, indicating that under conditions of water stress, the stomata closed to decrease the transpiration, and save water. Stomatal closure was the main reason for the decline in P_n under conditions of water stress. Under the RT treatment, the lower SWC and gLAI resulted in a decrease of P_n, which may be due to the deficiency of soil water and N content in the soil [36]. Moreover, SS treatment had a positive effect on F_v/F_m. The SS treatment improved both P_n and chlorophyll fluorescence characteristics in the growing season, especially in the later growing season, which resulted in higher grain filling characteristics in the grain-filling stage.

4.2. Subsoiling Practice to Increase Grain Yield and WUE

Optimum canopy function is a key factor in achieving a higher yield. Photosynthesis supplies carbohydrates for maize DMA and grain yield formation [7]. Previous studies have shown that without supplemental irrigation throughout the whole growing season, the SS practice can improve grain yields by up to 46% compared to conventional tillage. However, under irrigation conditions, there is no significant difference between the SS and conventional tillage treatments [15,37]. Our study in yellow cinnamon soil showed that the SS + I treatment decreased the DMT to the grain and the contribution of DMT to the grain before the silking stage. However, the SS + I treatment enhanced the DMA and increased the contribution of DMA to the grain at the post-silking stage. This phenomenon may occur due to the higher gLAI and P_n in the grain-filling stage, accompanied by an increase in the grain-filling rate in the later reproductive stage and longer grain-filling duration, especially the middle grain-filling period, which resulted in the higher DMA at the post-silking stage and had a strong influence on the yield formation, which is consistent with the results of Zhai [1]. However, long-term RT treatment caused high soil bulk density, which affects the soil microbial populations and enzyme activities and limits both root growth and uptake of moisture and nutrients, ultimately affecting crop growth and productivity [18,22,38]. The availability of soil water for plants is a major determinant in the yield potential [39]. Our results showed that with the decrease in soil bulk density, the SWC in the deep soil layer increased and WUE was enhanced, which may occur because SS, as a proper tillage practice, is able to break up the plow pan [40,41].

Consequently, our results indicate that the SS treatment can improve the soil water content in the deep soil layer, which then increases the gLAI, P_n, post-silking DMA and DMT, grain-filling rate and grain-filling duration, thereby improving the grain yield and WUE. When the seasonal rainfall distribution is inconsistent, the practice of SS may alleviate heat and drought damage, and improve the maize growth, which reduces the input cost [42]. However, the annual SS practice may increase the mechanical operation consumption, regardless of the agronomic input cost, compared with the RT practice. Therefore, in the future, we will further research new tillage modes, for example, one year of SS practice plus one year of no tillage practice, or a longer no tillage practice in order to reduce the input costs. Additionally, we will further our research on the root and nitrogen content in the soil profile response to the different tillage practices to confirm our hypothesis.

5. Conclusions

The SS practice decreased the soil bulk density, enhanced SWC in the soil, and improved gLAI and P_n. Under RT treatment, which may cause water stress, stomatal closure is the main reason for the decline in P_n. Applying supplemental irrigation under RT treatment can compensate for this via the improved growth of leaves, although it still cannot reverse the decreasing trend. Ultimately, the SS treatment improved the WUE, which resulted in an increase in grain yield.

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