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Article

Maize canopy photosynthesis, plant growth, and yield responses to tillage depth

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Abstract: Subsoil tillage loosens compacted soil for better plant growth, but promotes water loss, which is a concern in areas commonly irrigated. Therefore, our objective was to determine the physiological responses of high yield spring corn (Zea mays L.) to Subsoil tillage depth when grown in the western plain irrigation area of Inner Mongolia that leads to the best water use efficiency. The experiment during 2014 and 2015 used Zhengdan958 and Xianyu335 with three differing subsoil tillage depths (30, 40, or 50 cm) as trial factor and shallow rotary as a control. Subsoil tillage increased shoot dry matter accumulation, leading to a greater shoot/root ratio. Subsoil tillage helped retain greater leaf area index in each growth stage, increase the leaf area duration, net assimilation rate, and relative growth rate, with greater effects as tillage was deeper, effectively delaying the aging of the blade. Grain yields were increased by 0.7%-8.9% on average in subsoil tillage treatments compared to conventional soil treatment shallow rotary, Water use efficiency were increased by 1.93%-18.49% on average in subsoil tillage treatment compared to shallow rotary, resulting in net income increases by 2.24% to 6.97% compared to shallow rotary. Among the three different subsoil tillage depth treatment, the grain yield, water use efficiency, and net income is the best under the treatment of subsoil tillage depth of 50cm.

Keywords: chiseling depth; spring corn; canopy characteristics; photosynthesis quality

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1. Introduction

Soil is an important carrier of crop growth, and improving soil quality can effectively improve crop yield. Crop yields, in turn, are directly affected by the quality of the ploughing layer. The average effective plough layer of the irrigated area in the Inner Mongolia Plain is only 15.1 cm, which is less than China's average value of 16.5 cm and far shallower than that of North America, which has an average effective plough layer of 35 cm. As maize roots are mainly distributed in the soil layer of 3-35 cm [1], the compacted soil not only restricts the development of plant roots, but also hinders the absorption of mineral nutrients and water by plants, reduces the production capacity of plant canopy, and limits the high grain yield [2, 3]. Therefore, appropriate soil tillage measures are of great significance for improving soil physical and chemical properties, farmland soil quality, and maize photosynthesis characteristics.

Canopy structure greatly influences leaf photosynthetic rate [4]. There have been many studies on the canopy structure and physiological characteristics of corn in Inner Mongolia and abroad [5-8]. Leaves are the main organs for photosynthesis, which account for about 95% of the total in corn. Theoretically, if the photosynthetic duration is extended at maturity, yield can be increased by about 1% [9, 10]. The rate of photosynthesis and grain filling in plants are directly affected by leaf area duration and also leaf area index (LAI), the latter which represents the amount of leaf area and is an important quantitative index of canopy structure [11-13]. Leaf

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senescence is dependent on LAI, the higher LAI, the less senescence of corn leaves. Within a certain range, the larger the LAI, the greater the solar utilization efficiency [14-16]. A decrease in LAI may seriously affect grain number and weight during the filling stage [17, 18]. Bi Song et al. [19] showed that LAI increased with increased plant density from the jointing stage to the twelve-leaves stage, and peaked at the silking stage, which laid a foundation for the accumulation of dry matter in the later period of flowering. Li,S.Peng,Y.F.and Yu,P, etc. proposed that modern corn varieties had longer growth periods, larger leaf areas, and slower leaf senescence, leading to a significantly increased dry matter accumulation rate compared to early varieties, which indicated that dry matter accumulation is closely related to leaf senescence [20]. Dry matter accumulation directly affected the corn yield, which can be improved by increasing the dry matter production rate and duration.

In this paper, we investigated the effects of different chiseling depths on the photosynthesis characteristics of spring corn canopy, focusing on the soil conditions in the irrigated area of Inner Mongolia Plain. The results provided a theoretical basis and practical guidance for determining suitable chiseling depth for high-yielding spring corn in the western irrigation plains of Inner Mongolia and improving the planting management level of spring corn.

2. Materials and Methods

2.1 Experimental site

The field experiment was conducted during 2014 to 2015 in Hulutou village and Zhuergedai village, Salaqi Town, Tumd Right Banner, Baotou, Inner Mongolia, China. The region, located in the Tumochuan plain, has a typical continental semi-arid monsoon climate and receives an annual precipitation of 346 mm. The annual mean temperature of this area is 7.5 °C, and maximum temperatures occurred in July (average 22.9 °C). The region experiences 135 d frost-free days and average 3095 h annual sunshine hours. Drought is the main factor that affected yield in 2015. The precipitation in 2014 and 2015 varied greatly but the monthly mean temperature was similar between years (Figure 1).

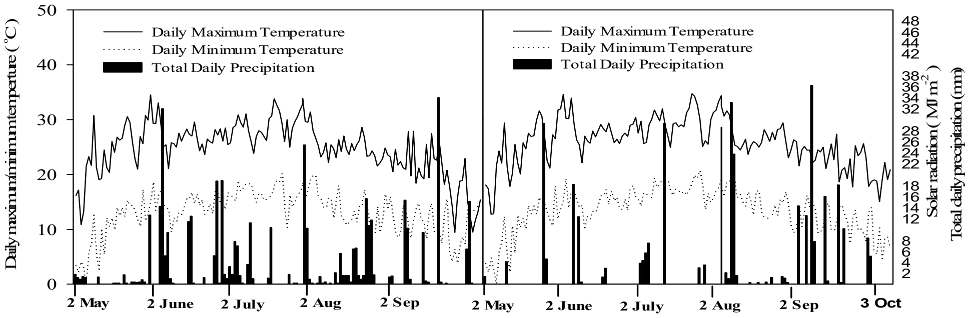

Figure 1. Precipitation and monthly average temperature at the study site during 2014-2015.

In 2014, the soil of the experimental site was sandy in texture, having pH 8.2, organic carbon 7.3 g·kg–1, available N 73.45 mg·kg–1, available P 15.1 mg·kg–1, and available K 120.4 mg·kg–1. In 2015, the soil of the experimental site was sandy in texture, having organic carbon 7.6 g·kg–1, available N 77.05 mg·kg–1, available P 14.05 mg·kg–1, and available K 118.8 mg·kg–1. The preceding crop in the experimental field which is subjected to conventional shallow tillage for a long time is spring maize, and the maize stalks were shredded and returned to the field after the corn was harvested.

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2.2 Experimental treatments and design

Subsoil tillage depth (30 cm, 40 cm and 50 cm, designated CH30, CH40, or CH50, respectively) was the trial factor, and compared to a control of shallow rotary (SR). In 2014, the tested variety was Xianyu335 with row distance of 50 cm and a plant density of 82500 plants per ha. Each subplot was area of 125 m2, 5 m wide and 25 m long with three replications, for a total of 12 plots in a randomized block arrangement. A split-plot design was used for the experiment in 2015, with subsoil tillage depth (30 cm, 40 cm, 50 cm and control as the main factor and variety (Xianyu335 and Zhengdan958) as the sub-factor. A plant density of 82500 per ha and row distance of 50 cm were used. Each subplot comprised of an area 125 m2, 5 m wide and 25 m long with 3 replications, for a total of 24 plots. All in-crop fertilizer of NPK was applied at planting (N: 200 kg/hm2, P2O5: 105 kg/hm2 and K2O: 62 kg/hm2) . Phosphate fertilizer and potash fertilizer were applied as basal fertilizer once before planting and nitrogen fertilizer was applied by 30% (60 kg/hm2)atV6 stage(six leaves with collars visible) and 70%(140 kg/hm2) at V12 stage(twelve leaves with collars visible) respectively. Irrigation and other management measures during the whole growth period were similar to local farmer practices. Record the precipitation and the irrigation rate during the growth stage.

2.3 Measured parameters

2.3.1 Leaf area

Plants were sampled at five growth stage: V6 stage (six leaves with collars visible),V12 stage (twelve leaves with collars visible),R1stage (silking stage),R3 stage filling stage) and R6 stage (physiological maturity) by three areas each plot, and in each area, three continuous plants (9 plant per plot) were sampled.

Leaf length and leaf width were measured to calculate leaf area, It was measured atV6, V12, R1, R3, and R6 respectively.

$$A1=0.75\times \text{Leaf Length} \times \text{Leaf width} \quad (1)$$

$$A2= 0.5\times \text{Leaf Length} \times \text{Leaf width} \quad (2)$$

Where A_1 was area of expanded leaves and A_2 represented area of unexpanded leaves.

2.3.2 Accumulation and transport of dry matter

At V6 stage, V12stage, R1stage, R3stage and R6 stage, take three sample area in each plot, three uniform plants per area were selected and divided into four parts: leaf, stem and sheath, female ear and grain. At the R1 stage, corresponding roots were examined in the depth of 0-60cm. Fresh samples were killed at 105 °C for 30 minutes, and dried at 80 ℃ to a constant weight in a oven.

2.3.3 Production of photosynthesis

Leaf area duration (LAD), net assimilation rate (NAR) and relative growth rate (RGR) were calculated by the following formula:

$$LAD[\,(m^2\cdot d)/hm^2]=[(L1+L2)/2]\times(t2- t1) \quad (3)$$

$$NAR[g/(m^2\cdot d)]=[(\ln L2- \ln L1)\times(W2- W1)]/[(L2- L1)\times(t2- t1)] \quad (4)$$

$$RGR[g/(kg\cdot d)]=(\ln W2- \ln W1)/(t2- t1) \quad (5)$$

where L1 and L2 were leaf area at time t1 and t2, respectively; W1 and W2 were dry matter weight at time t1 and t2, respectively.

2.3.4 Stover biomass and Grain yield

To evaluate Stover biomass and grain yield of Maize, plants were sampled at R6 stage. sampling

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consisted of manually excising plants from the center two rows of each plot at R6 (three sample area each plot, each sample area six continuous plants,eighteen plants per plot) to determine the stover biomass . The plants at R6 were partitioned into grain and stover (including husk) components, the total fresh stover were dried to 0% moisture and then weight. Corn ears were weighed to obtain grain and cob weight, The grain was removed manually to analyzed for moisture content using seed moisture meter (PM-8188-A,KETT ELECTRIC LABORATORY, Japan), the cob and the grain were dried and weight again. dry stover and dry cob weights were summed to calculate the overall R6 stover biomass. 300 randomly selected kernels were weighed to estimate average individual kernel weight, Kernel number was estimated by dividing grain yield by the average individual kernel weight of each plot, kernel number per corn ear was estimated by dividing kernel number by the number of the corn ear of each plot. All biomass and grain weight measurements are presented on a 0 % moisture concentration basis.

Plant stand counts were tallied to confirm plant populations at the R6 plant growth stage. and ear stand counts were tallied to confirm ear number per hm2.The center two rows of each plot were manually harvested for determination of grain yield at physiological maturity, and yield values are presented at 0% moisture concentration too.

2.3.5 Water Use Efficiency (WUE) and Water Production Efficiency (WPE)

2.3.5.1 $$\mathrm{WUE}(\mathrm{kg/\ hm^2 \cdot mm}) = \mathrm{GY/ET} \quad (6)$$

Where WUE were water use efficiency, GY were the grain yield, ET were Maize water consumer.

2.3.5.2 $$\mathrm{WPE}(\mathrm{kg/\ hm^2 \cdot mm}) = \mathrm{BY/ET}$$

Where WPE were water production efficiency, BY were the biomass yield, ET were Maize water consumer.

2.3.5.3 $$\mathrm{ET} = \mathrm{P}+\mathrm{I}+\triangle\mathrm{SWS} \quad (7)$$

Where ET were Maize water consumer, P were precipitation during the growth stage, I were irrigation rate during the growth stage, △SWS were the balance between soil pondage in the sowing time and the harvest time.

2.3.5.4 $$\mathrm{SWS} = \text{Soil depth} \times \text{Soil volume weight} \times \text{Soil moisture} \quad (8)$$

At sowing time and harvest time, 0-100cm depth soil were sampled to measure the soil volume weight and soil moisture, five area each plot, using the cutting ring to sample in 0cm-20cm,20cm-40cm,40cm-60cm,60cm-80cm and 80cm-100cm soil , three cutting ring each soil layer. weight the fresh weight, excavate the soil from the cutting ring ,and put the soil into oven to dry to 0% moisture, weight again ,measure the volume of the cutting ring, calculate the soil moisture and soil volume weight.

2.4 Statistical analysis

Analysis of variance (ANOVA) was used to evaluate treatment effects. data of Biomass accumulation, leaf area index, Dynamics of leaf area duration, Net assimilation rate, Relative growth rate, maize yield, yield components and economic benefit were analyzed using variance analysis of SAS[21]. Pearson's correlation coefficient was used to evaluate the linear association between grain yield and measured parameters across all treatments and within each rotation, using the CORR procedure of SAS.

3. Results

3.1 Effect of subsoil tillage depth on dry matter accumulation of maize

With the development of growth stage, the accumulation of dry matter gradually increased. In 2014, subsoil tillage treatment was significantly higher than that of the control in all the growth periods except for the V12 stage. in V6 stage,V12 stage,R1 stage,R3 stage and R6 stage, plants grown with CH50 tillage had greater dry matter accumulation than the control by 78.33%、16.48%、13.63%、56.61% and 20.79%, respectively; CH40 tillage increased plant growth by 51.46%、2.56%、13.11%、29.76% and 7.20% compared to the control. And CH30 is the same as aforementioned groups, overtopping SR in 35.00%, 4.01%, 24.06%, 23.69% and 8.75%(Tab.1). Deeper subsoil tillage led to increasingly greater total dry matter than that of the control.

Table 1. Effect of subsoil tillage treatments on the accumulation of Xianyu335 dry matter at different growth stages in 2014. Values are the average ± 1 standard error.

Stage	Treatments	dry matter (g per plant)				Increased compared to control(%)
		Stem	Leaf	Ear	Total	
V6	CH50	†37.8 ± 1.13a	†47.8±6.01a	—	†85.6±7.24a	78.33
	CH40	33.3±4.82b	39.5±3.03b	—	72.7±7.85b	51.46
	CH30	29.2±6.32b	35.6±4.18c	—	64.8±5.24b	35.00
	SR	19.3±1.90b	28.7±0.38c	—	48.0±2.28c	--
V12	CH50	59.6±4.92a	45.0±0.96a	—	104.6±5.88a	16.48
	CH40	53.5±7.25b	38.6±4.92b	—	92.1±6.62b	2.56
	CH30	52.2±5.98b	41.2±2.11b	—	93.4±5.28b	4.01
	SR	50.9±5.77c	38.9±3.62b	—	89.8±8.22b	--
R1	CH50	127.1±2.39a	55.9±4.15a	†37.2±5.44a	220.1±6.54b	13.63
	CH40	125.2±7.49b	55.5±7.91a	38.4±7.03b	219.1±7.11b	13.11
	CH30	122.6±2.79c	66.0±1.68b	51.7±4.51c	240.3±4.47a	24.06
	SR	114.6±5.08c	50.7±1.96b	28.4±1.61b	193.7±3.57c	--
R3	CH50	176.0±2.80a	62.9±1.96a	192.2±7.82a	431.0±7.14a	56.61
	CH40	148.5±5.75b	56.4±6.82b	152.1±2.36b	357.1±9.18b	29.76
	CH30	136.2±2.89a	49.3±3.62b	155.0±4.67b	340.4±8.29b	23.69
	SR	112.1±2.99c	46.2±5.41c	116.9±4.59c	275.2±8.40c	--
R6	CH50	146.3±5.47a	49.5±3.94a	304.0±2.66a	499.7±4.9.41a	20.79
	CH40	120.4±6.89a	44.4±2.30a	278.7±2.04b	443.5±10.16b	7.20
	CH30	116.8±3.16a	48.4±0.60a	284.7±0.51a	449.9±7.29b	8.75
	SR	106.8±5.02a	46.1±9.03b	260.8±6.57b	413.7±11.24c	--

† Means within a column and growth stage followed by the same letter are not significantly different at *P* ≤ 0.05, and the different letter are significantly different at *P* ≤ 0.05.

In 2015, the growth performance trend of the two varieties was consistent with that of 2014. Deeper subsoil tillage led to increasingly greater total dry matter accumulation than that of the control. Tillage of subsoil tillage treatment was significantly higher than that of the control in most the growth periods.

In V6 stage,V12 stage,R1 stage,R3 stage and R6 stage, Xianyu335 treated with CH50 tillage had greater dry matter accumulation than the control by 50.58%、21.98%、19.91%、23.70% and 5.09%, respectively; CH40 tillage increased plant growth by 12.21%、8.55%、11.23% and 10.55% in v6 stage,V12 stage,R1 stage and R3 stage compared to the control, and make no significant difference between the control in R6 stage; CH30 is the same as aforementioned groups, overtopping SR in 6.20%,9.16%, 17.42%, and 3.55% in V6stage、V12stage、R3stage and R6stage,and make no significant difference between the control in R1 stage(Tab.2).

Table 2. Effect of subsoil tillage treatment on the accumulation of Xianyu335dry matter at different growth stages in 2015. Values are the average ± 1 standard error.

Stage	Treat ments	dry matter (g per plant)				Increased compared to control(%)
		Stem	Leaf	Ear	Total	
V6	CH50	†37.4±5.26a	†40.3±4.44a	—	†77.7±4.24a	50.58
	CH40	26.5±4.67b	31.4±4.50b	—	57.9±8.43b	12.21
	CH30	25.7±5.44b	29.1±7.05c	—	54.8±10.49b	6.20
	SR	23.3±4.20b	28.4±4.81c	—	51.6±9.01b	--
V12	CH50	53.7±8.34a	46.2±2.49a	—	99.9±8.83a	21.98
	CH40	49.9±3.97b	39.1±3.45b	—	88.9±6.45b	8.55
	CH30	47.6±4.94b	41.8±1.34b	—	89.4±5.28b	9.16
	SR	43.5±1.37c	38.4±1.88b	—	81.9±3.25c	--
R1	CH50	86.5±4.85a	43.5±2.89a	†48.3±3.00a	178.3±7.74a	19.91
	CH40	79.5±2.79b	42.8±6.14a	43.3±9.08b	165.4±8.93b	11.23
	CH30	73.7±7.04c	36.7±2.52b	30.3±3.31c	140.8±4.04c	--
	SR	73.5±1.57c	36.8±5.13b	38.4±7.88b	148.7±6.74c	--
R3	CH50	91.1±8.50a	49.7±5.65a	111.3±7.82a	252.1±7.14a	23.70
	CH40	82.3±3.38b	41.3±4.45b	101.8±2.60b	225.3±7.83b	10.55
	CH30	91.0±2.96a	44.6±6.30b	103.7±9.70b	239.3±9.26b	17.42
	SR	73.8±7.21c	36.6±8.85c	93.4±4.87c	203.8±7.26c	--
R6	CH50	71.6±6.61a	41.6±7.00a	254.1±3.03a	367.2±4.64a	5.09
	CH40	62.1±5.96a	41.7±3.20a	243.7±5.75b	347.5±9.16b	--
	CH30	68.6±3.16a	40.8±8.80a	252.5±4.13a	361.8±7.29a	3.55
	SR	68.6±1.47a	37.1±5.77b	243.7±7.01b	349.4±7.24b	--

† Means within a column and growth stage followed by the same letter are not significantly different at $P \le 0.05$, and the different letter are significantly different at $P \le 0.05$.

Dry matter accumulation of Zhengdan958 under the treatments of CH50 was improved by40.99%, 37.37%, 24.77%,9.95% and 10.19% respectively in V6stage、V12stage、R1stage、R3 stage andR6 stage, compared with the control; Dry matter accumulation of Zhengdan958 under the treatments of CH40 was improved by56.70%, 16.56%, 18.48%,5.14% and 12.97% respectively in V6stage、V12stage、R1stage、R3 stage andR6 stage, compared with the control; Dry matter accumulation of Zhengdan958 under the treatments of CH30 was improved by30.08%, 8.07%, 19.61%,6.20% and 10.44% respectively in V6stage、V12stage、R1stage、R3 stage andR6 stage, compared with the control(Tab.3).

The results of the two years experiment showed that subsoil tillage could increase dry matter accumulation and lay a foundation for greater grain fill and increased yield. The response of dry matter accumulation by Xianyu335 to subsoil tillage depth was more obvious than the response by Zhengdan958 (Table2-3).

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Table 3. Effect of subsoil tillage treatment on the accumulation of Zhengdan958 dry matter at different growth stages in 2015. Values are the average ± 1 standard error.

Stage	Treatments	dry matter (g per plant)				Increased compared to control(%)
		Stem	Leaf	Ear	Total	
V6	CH50	†34.9±4.76b	†38.7±6.04b	—	†73.6±5.84b	40.99
	CH40	39.3±5.68a	42.5±4.54a	—	81.8±9.45a	56.70
	CH30	32.8±9.87b	35.0±6.37b	—	67.9±6.49b	30.08
	SR	24.9±4.87c	27.2±4.53c	—	52.2±7.55c	--
V12	CH50	85.9±7.43a	43.5±7.14a	—	129.4±7.14a	37.37
	CH40	63.6±5.27b	46.2±1.80a	—	109.8±6.07b	16.56
	CH30	55.1±2.69c	46.7±6.05a	—	101.8±8.74b	8.07
	SR	53.7±6.72c	40.5±6.75a	—	94.2±7.72c	--
R1	CH50	75.6±5.96a	41.1±5.69a	†48.7±3.94a	165.4±8.69a	24.74
	CH40	70.4±5.41a	40.7±7.35a	46.1±5.56a	157.1±6.56b	18.48
	CH30	72.7±3.52a	37.4±3.35b	48.5±3.59a	158.6±6.87b	19.61
	SR	63.0±5.87b	30.5±1.58c	39.1±5.29b	132.6±6.77c	--
R3	CH50	75.2±8.80a	37.7±3.11b	115.9±2.90a	228.7±6.01a	9.95
	CH40	74.4±2.21a	39.4±5.54b	104.9±3.46b	218.7±5.67a	5.14
	CH30	72.6±4.09a	43.7±5.01a	104.6±3.64b	220.9±7.73a	6.20
	SR	68.2±2.60b	37.0±5.62b	102.8±7.07b	208.0±8.22b	--
R6	CH50	66.1±1.44a	43.6±8.41a	247.0±9.07b	356.7±6.85b	10.19
	CH40	64.5±6.60a	45.6±8.18a	255.5±3.56a	365.7±9.78a	12.97
	CH30	67.7±9.30a	37.2±3.86b	252.6±3.39a	357.5±6.39b	10.44
	SR	62.4±7.49a	35.3±4.81b	226.0±7.35c	323.7±7.48c	--

† Means within a column and growth stage followed by the same letter are not significantly different at $P \leq 0.05$, and the different letter are significantly different at $P \leq 0.05$.

3.2 Effects of Subsoil tillage depth on leaf area index of maize

The size of green leaf area directly affects the photosynthetic ability of plants and is an important index to determine the yield. All plants reach maximum LAI at R1 stage, which then gradually decreased (Figures 2, 3 and 4).

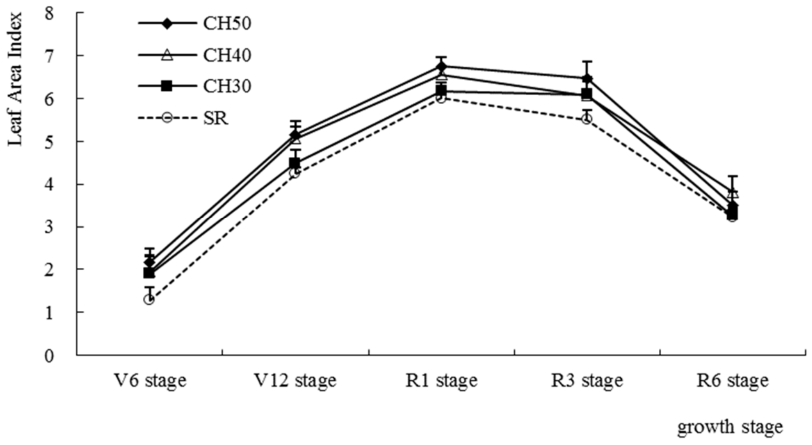

Figure2. The change of the leaf area index due to subsoil tillage depth for variety Xianyu335 in 2014. Values are the average of three replications. Bars indicate ± 1 standard error of the mean.

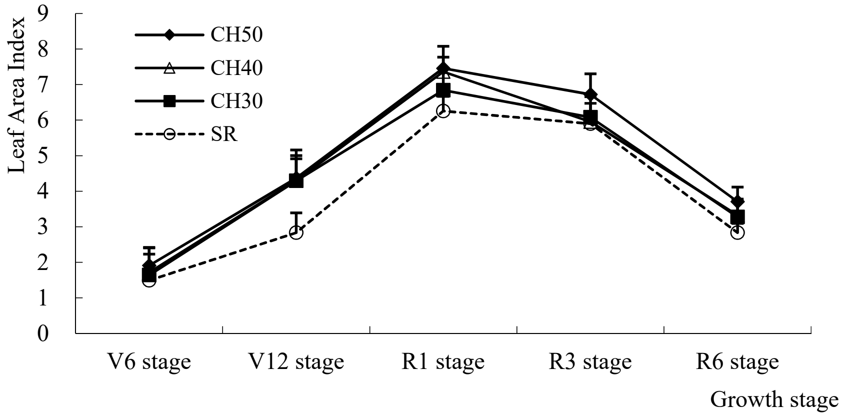

Figure 3. The change of Xianyu335 leaf area index due to subsoil tillage depth treatment in 2015. Values are the average of three replications, and bars represent± 1 standard error of the mean.

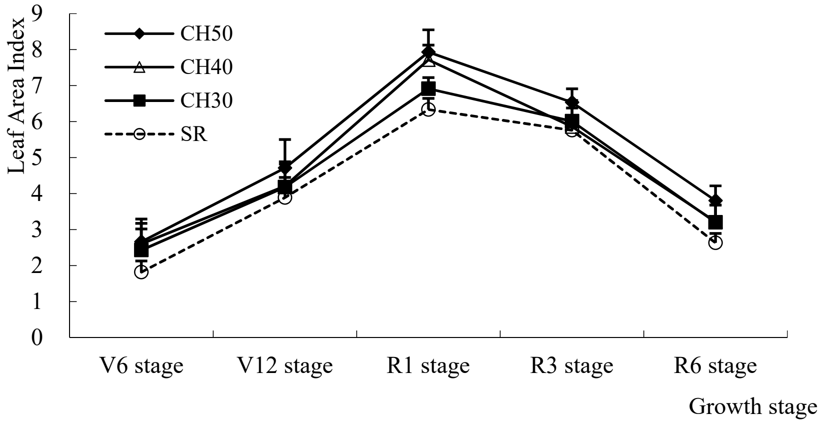

Figure4. The change of Zhengdan958 leaf area index due to subsoil tillage treatment in 2015. Values are the average of three replications, and bars represent ± 1 standard error of the mean.

The results over the two years showed that CH50 led to significantly greater LAI than the control. The CH40 treatment, led to greater LAI than the control over the whole growth period except in the R3 stage in 2015. The CH30 treatment lead to greater LAI than the control, except in the V12 stage and R1 stage in 2014, and inR3 stage in 2015, with no-significant differences between the control, At the other growth stages, CH30 treatment led to greater LAI than the control. The results showed that subsoil tillage depth could lead to maintenance of a relatively high leaf area index at different stages, and more prolonged LAI with increasing subsoil tillage depth, which provided the possibility for plants to capture more light for photosynthesis.

The leaf area index of Zhengdan958 was greater than that of Xianyu335 from theV3 stage to the R1 stage, but less than that of Xianyu335 after the R1 stage, indicating that the leaf senescence of Zhengdan958 was faster than that of Xianyu335 after the R1 stage.

.3 Dynamics of leaf area duration

Photosynthetic productivity was not only related to leaf area index, but also to leaf area duration (LAD). The duration of leaf area reflects the photosynthesis time of maize, so it has great influence on yield, because the grain is primarily composed of starch. Table 4 shows that there was a significant difference between the three subsoil tillage depth treatments and the control after silking, and overall LAD due to CH50 > CH40 > CH30. Leaf area duration from the CH50 treatment was significantly greater than that of CH40 or CH30; and there was a smaller difference of LAD between the CH40 and CH30 treatments. The leaf area duration from silking stage to filling stage was sustained the best during the growth stage, then it began to decrease, and the decrease from the filling stage to maturity was more pronounced; with no difference between the two varieties in LAD response to subsoil tillage depth.

Table 4. Dynamics of leaf area duration under different chiseling depth for two maize varieties grown in 2014 and/ or 2015. Values are the average ± 1 standard error.

Year Varieties	Treatment	Dynamics of leaf area duration [$10^4 m^2/(d \cdot hm^2)$] V6 stage-V12 stage	V12 stage-R1 stage	R1 stage-R3 stage	R3g stage-R6 stage
2014 Xianyu335	CH50	†3.1±0.19a	†13.0±1.09a	†17.6±1.14a	†12.7±0.56a
	CH40	3.0±0.13a	12.7±1.01a	16.9±0.79b	12.6±1.19a
	CH30	2.7±0.14a	11.6±0.63a	16.4±0.58b	11.9±0.89b
	SR	2.4±0.19a	11.2±1.18a	15.4±0.49c	11.1±0.75b
2015 Xianyu335	CH50	2.7±0.22a	12.9±0.59a	18.9±1.03a	13.3±0.79a
	CH40	2.6±0.19a	12.7±0.19a	17.8±1.21b	11.8±1.13b
	CH30	2.5±0.21a	12.2±0.89a	17.2±1.37b	11.9±1.07b
	SR	1.8±0.29b	9.9±0.75b	16.2±0.89c	11.1±0.87b
2015 Zhengdan958	CH50	3.1±0.16a	13.8±0.97a	19.3±1.10a	13.2±0.56a
	CH40	2.9±0.20a	13.0±0.89a	18.1±1.15b	11.6±0.67b
	CH30	2.8±0.09a	12.1±1.19b	17.2±0.97b	11.7±0.71b
	SR	2.4±0.09a	11.2±1.06b	16.1±0.94c	10.7±0.55c

† Means within a column and year variety followed by the same letter are not significantly different at *P* ≤ 0.05,and the different letter are significantly different at *P* ≤ 0.05.

3.4 Net assimilation rate

From Table 5, compared with the control, there was a significant difference in NAR between V6 stage to V12 stage due to subsoil tillage depth treatment, which showed that CH50 < CH40 < CH30 < SR, which reflected the rapid recovery of plant growth in this period due to the restriction of early growth.

Table5. Dynamics of net assimilation rate between plant stages when grown under different chiseling depth. Values are the mean of three replications ± 1 standard error.

Year Varieties	Treatment	Dynamics of net assimilation rate [$g/(m^2 \cdot d)$] V6 to V12 stage	V12stage to R1 stage	R1 stage to R3 stage	R3 stage to R6 stage
2014 Xianyu335	CH50	†13.3±1.19c	†5.8±0.19a	†5.4±0.59a	†5.6±0.44c
	CH40	14.2±1.01c	6.9±0.13a	5.4±0.19a	7.0±0.28c
	CH30	19.0±0.63b	6.3±0.14a	4.3±0.49b	9.5±0.31b
	SR	29.4±1.18a	5.8±0.19a	4.6±0.38b	12.7±0.52a
2015 Xianyu335	CH50	8.8±0.59c	6.2±0.22a	4.9±0.44a	8.9±0.42c
	CH40	13.0±0.79b	6.2±0.19a	4.4±0.58a	10.6±0.57b
	CH30	14.8±0.75b	7.3±0.31a	5.7±0.42a	10.6±0.36b
	SR	17.1±0.89a	7.9±0.35a	3.4±0.39b	13.7±0.31a
2015 Zhengdan958	CH50	11.1±0.97b	3.1±0.49a	3.3±0.41a	10.0±0.46b
	CH40	9.9±0.89c	3.8±0.52a	3.4±0.56a	13.1±0.29a
	CH30	12.4±1.12b	4.8±0.55a	3.6±0.35a	12.0±0.19a
	SR	18.2±1.06a	4.4±0.25a	2.8±0.39b	13.3±0.27a

† Means within a column and year variety followed by the same letter are not significantly different at P ≤ 0.05,and the different letter are significantly different at P ≤ 0.05.

There was no significant difference between the treatments from theV12 stage to R1 stage on plant NAR, which indicated that the vegetative growth of the treatment was stable, so the difference between the treatments was not obvious, and the NAR from the R1 stage to R3 stage was clearly higher than that of the control. And the subsoil tillage treatment showed the greater advantages than the control. It indicates that during the reproductive stages, the NAR of all the subsoil tillage depth treatment increased because of the increase of the filling rate, and the performance of the subsoil tillage depth treatment from the R3 stage to R6 stage was significantly lower than that of the control. The two varieties in 2015 had similar responses of NAR to tillage depth.

3.5 Relative growth rate

Relative growth rate (RGR) refers to net biomass generated per unit time unit biomass. Dry matter accumulation is directly related to relative growth rate [22].

Table 6 shows that the relative growth rate and net assimilation rate of maize have the same trend. Furthermore, the relative growth rate is greatest from the V6 stage to the V12 stage, and then decreases. Subsoil tillage did not affect the relative growth rate between most measured stage, except from the V6 stage to V12 stage , Subsoil tillage decreased RGR compared to the control. This difference was due to the control plants exhibiting a short-term accelerated growth trend from the V6 stage to V12 stage, but the control has less dry matter at V12 stage and then R6 stage due to less dry matter before V6 stage. the growth of all treatment mMaize in the early stage was faster than that in the later stage, and the dry matter accumulated rapidly in the early stage, which laid a foundation for the establishment of yield.

Table 6. Dynamics of relative growth rate under different chiseling depth Values are the mean of three replications ± 1 standard error.

Year Varieties	Treatment	Dynamics of relative growth rate(g/ (g·d)).			
		V6 stage to V12 stage	V12stage to R1stage	R1 stage to R3 stage	R3 stage to R6 stage
	CH50	†0.05±0.01b	†0.03±0.00a	†0.04±0.01a	†0.02±0.01a
2014 Xianyu335	CH40	0.06±0.01b	0.03±0.01a	0.03±0.01a	0.01±0.00a
	CH30	0.08±0.00b	0.04±0.01a	0.02±0.00a	0.01±0.01a
	SR	0.12±0.03a	0.03±0.00a	0.02±0.01a	0.02±0.01a
	CH50	0.04±0.01c	0.03±0.01a	0.02±0.01a	0.02±0.01a
2015 Xianyu335	CH40	0.06±0.01b	0.04±0.01a	0.01±0.00a	0.02±0.01a
	CH30	0.07±0.02b	0.03±0.01a	0.02±0.01a	0.02±0.01a
	SR	0.07±0.01b	0.03±0.01a	0.01±0.01a	0.03±0.01a
	CH50	0.05±0.00b	0.02±0.01a	0.02±0.01a	0.02±0.01a
2015 Zhengdan958	CH40	0.04±0.01b	0.02±0.01a	0.02±0.01a	0.02±0.01a
	CH30	0.06±0.01b	0.03±0.01a	0.02±0.01a	0.02±0.01a
	SR	0.08±0.01a	0.02±0.01a	0.01±0.01a	0.03±0.01a

† Means within a column and year variety followed by the same letter are not significantly different at *P* ≤ 0.05,and the different letter are significantly different at *P* ≤ 0.05.

3.6 Effects of subsoil tillage depth on shoot- root ratio

Table 7 shows that the dry weight of stem, leaf, female ear and root increased significantly compared with that of shallow rotary tillage treatment in 2014. The dry weights of stem, leaf, female ear, and root of Xianyu335 plants receiving the CH50 and CH40 treatments in 2015, but not the CH30 treatment, increased significantly compared to those receiving the shallow rotary tillage treatment.

Table 7. Dry matter distribution in different organs and shoot root ratio in maize at the silking stage as affected by tillage treatment. Values are the mean of three replications ± 1 standard error.

Year Varieties	Treatment	Dry matter (g per plant)					Shoot / root
		†Stem	†Leaf	†Ear	†Shoot	†Root	
2014 XianYu 335	CH50	121.5±14.37b	54.5±3.34a	60.3±1.82a	236.3±18.31a	18.4±0.73a	12.84
	CH40	138.3±10.5a	54.3±4.14a	47.4±7.62b	240.0±16.71a	17.6±0.25a	13.64
	CH30	123.9 ±14.27b	49.2±4.55b	48.2±6.40b	221.3±6.34b	16.2±0.67b	13.66
	SR	102.0±16.04c	39.9±4.69c	37.4±2.40c	179.3±30.03c	16.1±0.33b	11.14
2015 XianYu 335	CH50	85.1±2.59a	33.5±2.89b	44.9±4.81a	163.6±16.29a	18.5±0.50a	8.84
	CH40	79.5±12.79a	42.8±6.14a	43.3±3.09a	165.6±22.32a	17.8±0.42ab	9.30
	CH30	63.7±9.12b	36.7±2.52ab	37.0±6.11b	137.5± 17.58b	17.2±0.92bc	7.99
	SR	63.5±7.73b	36.8±5.13ab	35.1±2.11b	135.3±5.22b	16.3±0.22c	8.30
2015 Zheng Dan958	CH50	75.6±5.96a	41.1±5.69a	48.7±3.94a	165.4±23.94a	19.5±0.34a	8.48
	CH40	70.4±5.41ab	40.7±7.35a	39.7±5.56b	150.8±18.17ab	18.6±0.75ab	8.11
	CH30	72.6±3.52b	37.4±3.35a	48.5±2.59a	158.6±16.19b	18.5±0.48b	8.57
	SR	63.0±5.88c	30.5±1.58b	39.1±5.29b	132.6±12.93c	17.4±0.58c	7.62

† Means within a column and year variety followed by the same letter are not significantly different at $P \leq$ 0.05,and the different letter are significantly different at $P \leq 0.05$.

However, the dry weight of stem, leaf, female ear and root of Zhengdan958 were significantly increased with tillage over those receiving the shallow rotary tillage treatment. The ratio of shoot-root of plants receiving the subsoil tillage depth treatments were greater than that from the shallow rotary tillage treatment, which indicated that the growth of shoot aboveground was more than that of root system, and therefore resulted in the accumulation of greater shoot aboveground and an increase in yield. The ratio of shoot -root in 2015 was lower than that in 2014, which was due to the drought in 2015. In this condition, the growth of crop was under water stress, the relative biomass of root system increases, so the ratio of shoot- root descended.[23].

3.7 Effects of subsoil tillage depth on maize yield and economic benefit

3.7.1 Effects of subsoil tillage depth on maize yield and its components

Table 8 shows that there are significant differences in area biomass accumulation and yield due to tillage depth. In 2014, subsoil tillage of CH50, CH40 and CH30 increased yields over that of the control (SR), by 6.9%, 3.5% and 3.5%, respectively, with an average increase of 4.6%. The biomass from CH50 tillage was 10.6% higher than that of the control, The CH50 tillage led to significantly greater biomass than that of SR. However, there was no significant difference in biomass between the CH40, CH30 and SR treatments. In 2015, the yield of the two varieties showed the same trend, with the subsoil tillage depth treatments generating greater yields than those receiving the shallow rotary tillage treatment. Subsoil tillage increased Xianyu335 yields by 3.7% to 8.9%, but there was no significant difference between the CH40 and CH30 treatments. the biomass in Subsoil tillage depth treatment was significantly higher than that of SR, with an average of 5.0%. While subsoil tillage treatments increased yield and biomass of Zhengdan958 over the control; they led to similar responses. Plants of CH50, CH40 and CH30 tillage treatment increased yield, on average, by 4.0%, 1.5% and 0.7%, respectively. In addition, the biomass of Zhengdan958 increased by 6.0%, 3.9% and 3.7% compared to the control. There was no significant difference among the three treatments in biomass.

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Table 8. Biomass, grain yield and yield components under different subsoiling treatments Values are the mean of three replications ± 1 standard error.

Year Varieties	Treat ment	t/hm^2		10^4/ hm^2	Per ear	g
		Biomass	Grain yield	Ear number	Kernel number	100-kernel weight
2014 Xianyu 335	CH50	†41.6±0.11 a	†15.4±0.26a	†7.67±0.03a	†646±24.12	†35.4±0.15 a
	CH40	38.4±0.72 b	14.9±0.14b	7.60±0.05 a	637±33.41 a	35.2±0.11 a
	CH30	37.9±0.72 b	14.9±0.11b	7.50±0.16 a	651±12.13 a	34.9±0.12 ab
	SR	37.6±0.54 b	14.4±0.16 c	7.62±0.19 a	656±5.76 a	34.5±0.34 b
2015 Xianyu 335	CH50	29.7±0.68 a	14.7±0.11a	8.80±0.01 a	618±16.94 a	31.7±0.09 a
	CH40	29.2±0.66 a	14.2±0.17b	8.44±0.25 a	610±11.15 a	31.9±0.13 a
	CH30	29.6±0.64 a	14.0±0.29b	8.51±0.18 a	607±11.32 a	32.8±0.12 a
	SR	28.1±0.45 b	13.5±0.13c	8.43±0.19 a	610±10.67 a	30.9±0.17 b
2015 Zhengdan 958	CH50	30.0±0.49 a	13.6±0.11a	8.65±0.06 a	589±12.15 a	31.3±0.14 a
	CH40	29.3±0.14 a	13.2±0.14a	8.49±0.18 a	574±9.98 a	31.8±0.18 a
	CH30	29.4±0.23 a	13.1±0.09a	8.44±0.16 a	573±19.56 a	32.2±0.10 a
	SR	28.3±0.54 b	13.0±0.1b	8.43±0.14 a	575±13.12 a	31.6±0.16 a

† Means within a column and year variety followed by the same letter are not significantly different at $P \leq 0.05$,and the different letter are significantly different at $P \leq 0.05$.

for the production components, The 100-grain weight of Xianyu335 was significantly increased by subsoil tillage depth treatment, but not for Zhengdan958.it indicate that the treatment of deepen the subsoil depth can lead significant increasing in the 100-grain weight of Xianyu335.but no significant increasing in Zhengdan958.

3.7.2 Correlation analysis between canopy characteristics and yield

Correlation analysis between canopy characteristics and yield showed that stover biomass dry matter and leaf area index were significantly positively correlated with yield (Table 9). The correlation coefficients of the stover biomass dry matter and leaf area index with yield were 0.972 and 0.952, respectively. The results showed that dry matter was the main factor affecting the grain yield.

Table9. Pearson correlation coefficients and associated significance level for final grain yield between selected corn canopy parameters as influenced by subsoil tillage depth

	Dry matter	Leaf area index	Grain yield
Dry matter	1.000		
Leaf area index	0.902**	1.000	
Grain yield	0.972**	0.952**	1.000

**** Significant at the 0.01 probability level.**

3.7.3 Effect of subsoil tillage depth on water use efficiency

Regardless of drought or wet and rainy years, plant water use efficiency (WUE) was significantly improved by subsoil tillage depth treatment (Table 10). In 2014, the treatments of CH50, CH40 and CH30 increased WUE by 14.62%, 8.29% and 6.92%, respectively. In 2015, CH50, CH40 and CH30 increased WUE of Xianyu335 by 18.49%, 8.74% and 9.53% respectively, and WUE of Zhengdan958 by 6.41%, 1.93% and 2.28% respectively, compared with the control. The two years of data showed that the CH50 treatment led to the highest WUE under the condition of the lowest water availability, followed by CH40 and CH30. However, CH40 and CH30 treatments similarly affected WUE, and there is no significant difference between the treatment of CH40 and CH30.

Table 10. Water use efficiency of spring maize under different tillage depth Values are the mean of three replications.

Year Varieties	Treatment	mm	kg/hm^2		kg/(hm^2·mm)	(kg/hm^2·mm)
		Water consume	Seed yield	Biological yield	Water use efficiency	Water productivity
2014 Xianyu335	CH50	†770.9bc	†15447 a	†41614 a	†20.04a	†53.98a
	CH40	786.6b	14891 b	38405 b	18.93b	48.83b
	CH30	796.2b	14883 b	37876 b	18.69b	47.57b
	SR	823.6a	14398 c	37551 b	17.48c	45.59c
2015 Xianyu335	CH50	540.7c	14660 a	29710 a	27.11a	54.95a
	CH40	562.1b	13985 bc	29196 a	24.88b	51.94b
	CH30	574.9b	14404 ab	29638 a	25.06b	51.56b
	SR	591.5a	13531 c	28100 b	22.88c	47.51c
2015 Zhengdan958	CH50	560.5b	13576 a	29993 a	24.22a	53.51a
	CH40	568.7b	13192 a	29319 a	23.20b	51.55b
	CH30	568.6b	13234 a	29374 a	23.28b	51.66b
	SR	573.3a	13048 b	28284 b	22.76c	49.34c

† Means within a column and year variety followed by the same letter are not significantly different at *P* ≤ 0.05,and the different letter are significantly different at *P* ≤ 0.05.

Maize water production efficiency (WPE) responses to tillage level were comparable to the WUE responses. In 2014, CH50, CH40 and CH30 increased WPE over the control by 18.40%, 7.11% and 4.34%; in 2015, the WPE of Xianyu335 increased by 15.66%, 9.32% and 8.52%, and Zhengdan958 WPE increased by 8.45%, 4.48% and 4.70%, respectively. The CH50 tillage increased WPE by 3.80% and 3.58% compared to CH40 and CH30 respectively, but WPE was not affected between the CH40 and CH30 treatments.

3.7.4 Economic benefit analysis

The depth of subsoil tillage is an important factor for farmers to consider the cost. Therefore, this experiment analyzed the economic input-output ratio for growing maize using the different tillage depths.

Table 11. Inputs and outputs of maize production for different treatments in the year 2014.

		CH50	CH40	CH30	SR
Inputs	Seeds (RMB/hm^2)	1050	1050	1050	1050
	Fertilizer (RMB/hm^2)	1600	1600	1600	1600
	Pesticides (RMB/hm^2)	1500	1500	1500	1500
	Irrigation (RMB/hm^2)	1200	1200	1200	1200
	Mechanical work (RMB/hm^2)	900	750	600	450
	Total (RMB/hm^2)	6250	6100	5950	5800
Outputs	Yield (kg/hm^2)	15447	14891	14883	14398
	Price (RMByuan/kg)	1	1	1	1
	Income (RMB/hm^2)	15447	14891	14883	14398
	Net income (RMB/hm^2)	9197	8791	8933	8598
	Increase (%)	6.97	2.24	3.90	

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Table 12. Inputs and outputs of maize production for different treatments in the year 2015.

		CH50	CH40	CH30	SR
Inputs	Seeds (RMB/hm²)	1050	1050	1050	1050
	Fertilizer (RMB/hm²)	1600	1600	1600	1600
	Pesticides (RMB/hm²)	1500	1500	1500	1500
	Irrigation (RMB/hm²)	1200	1200	1200	1200
	Mechanical work (RMB/hm²)	900	750	600	450
	Total (RMB/hm²)	6250	6100	5950	5800
Outputs	Yield (kg/hm²)	†14118	†13589	†13819	†13290
	Price (RMByuan/kg)	1	1	1	1
	Income (RMB/hm²)	14118	13589	13819	13290
	Net income (RMB/ ha)	7868	7489	7869	7490
	Increase (%)	5.05	--	5.06	

† Means within a column and subsoil tillage depth treatment and the control are average of Xianyu335 and Zhengdan958 in 2015.

The results are shown in Table 11-12.When averaged over the years, the net income increased due to increasing depths of subsoil tillage by 2.24% to 6.97% than that of the shallow rotary tillage treatment. Among them, subsoil tillage depth 50cm led to the highest returns, followed by tillage to a depth of 30cm. There was no significant difference between the yields from tilling to 40 cm versus 30 cm depths, but the cost of tiling down to 40 cm increased, resulting in a decrease in net income. The test results show that the most economic advantage is subsoil tillage to a depth of 50 cm. So, the results of this study can be used as a reference for people to choose the depth of subsoil tillage depth to reduce costs and increase income.

4. Discussion

4.1 The effect of subsoil tillage on corn canopy

It is generally thought that subsoil tillage could promote the absorption of N, P, and K by reducing the bulk density of the lower soil layer, thereby increasing nutrient availability so as to distribute more nutrients to the aboveground parts and promote the growth of corn. Without subsoil tillage, the soil has a large soil bulk density, the activity of superoxide dismutase in the leaves of corn decreased in the later growth period with a corresponding shortened functional leaf duration and quickened premature senescence [24, 25]. As the leaf area of the maize plants treated with subsoil tillage increased, the total dry matter accumulation amount and rate increased, especially at the later stage, the yield was significantly increased [26-29]. The yield of spring corn increased by 14.6% by subsoil tillage [30], which may have loosened soil, improved permeability, promoted dry matter accumulation of winter wheat and summer corn [31, 32], and in so doing, significantly improved grain yield and water utilization efficiency of crops [33-35]. This study indicated that subsoil tillage could maintain relatively high leaf area index in different growth periods and increase leaf area duration. The deeper the subsoil tillage, the longer it maintained plant health. Subsoil tillage effectively delayed leaf senescence, which provided the possibility for plants to capture more light for photosynthesis. The net assimilation rate and relative growth rate in the late silking period were significantly increased by subsoiling tillage compared to the control, with CH50 > CH40 > CH30. These results indicated that subsoil tillage was beneficial to the accumulation of dry matter in the early growth stage and laid a foundation for the formation of yield in the late growth period.

4.2 Response of different corn varieties to chiseling depth

The leaf area index of Zhengdan958 was higher than Xianyu335 from the V6 stage to the R1 stage, but lower than Xianyu335 after the R1 stage, indicating that the leaf senescence rate of Zhengdan958 was faster than that of Xianyu335 after R1 stage.

The water use efficiency of Xianyu335 and Zhengdan958 with subsoil tillage increased by 12.25% and 3.54% compared to the control, respectively, which indicated Xianyu335 was more sensitive to subsoil tillage depth than Zhengdan958. The results of this study indicated that different varieties had different responses to subsoil tillage depth, but whether different soil types, and climatic conditions had the same effect remains to be further studied [36].

The intensity of subsoiling tillage should be suitable to avoid economic efficiency descending [37]. Cai Hongguang [38] found that subsoil tillage of 50 cm was superior to that of 30 cm or no chiseling. Our study indicated that subsoiling tillage of 50 cm was optimal, and there was no significant economic difference between the 40 cm and 30 cm subsoil tillages.

5. Conclusions

Subsoil tillage can maintain relatively high leaf area index and increase leaf area duration. In this experiment, the deeper the subsoil tillage, the longer it lasted, and the senescence of leaves was effectively delayed, which made it possible to prolong the photosynthetic time of plants. Compared with the control, subsoil tillage significantly increased net assimilation rate and relative growth rate after the R1 stage, ordered from high to low values: CH50, CH40 and CH30.

There was a significant difference in yield among treatments, and the yield under subsoil tillage treatment was significantly higher (0.7% to 10.6%) than that of the control (SR). In terms of yield components, subsoil tillage significantly increased 100-grain weight of Xianyu335, while other factors had no significant difference. Correlation analysis between canopy parameters and yield showed that the correlation coefficients of dry matter ($r = 0.972$) and leaf area index ($r = 0.952$) with yield were very high, which indicated that dry matter was the main factor affecting the final yield. Considering the economic benefits, the net income of the CH50, CH40,and CH30 treatments were 2.24%-6.97% higher than that of shallow rotary tillage treatment, respectively, the best was the 50 cm subsoil tillage treatment.

Author Contributions: Ji-ying Sun and Ju-lin Gao conceived and designed the experiments; Feng-jie Zhang and Ya-fang Fan performed the experiments; Hai-zhu Bao performed the statistical analysis; Zhi-gang Wang and Shu-ping Hu analyzed the results; Ji-ying Sun wrote the paper.

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