Regulation of Subsoiling Tillage on the Grain Filling Characteristics of Maize Varieties From Different Eras

Li-qing WANG
Inner Mongolia Agricultural University
Xiao-Fang YU (nmyuxiaofang@imau.edu.cn)
Inner Mongolia Agricultural University
Ju-Lin GAO
Inner Mongolia Agricultural University
Da-Ling MA
Inner Mongolia Agricultural University
Liang LI
Inner Mongolia Agricultural University
Shu-Ping HU
Inner Mongolia Agricultural University

Research Article

Keywords: spring maize, subsoiling tillage, grain filling

Posted Date: March 1st, 2021

DOI: https://doi.org/10.21203/rs.3.rs-243081/v1

Regulation of subsoiling tillage on the grain filling characteristics of maize varieties from different eras

Li-qing WANG[1] , Xiao-Fang YU[1] *, Ju-Lin GAO [1]*, Da-Ling MA[1] , Liang LI[1] ,Shu-Ping HU[1]

1 Inner Mongolia Agricultural University, No.275, XinJian East Street, Hohhot 010019, China;
nmwangliqing@emails.imau.edu.cn (L.-Q.W.); nmyuxiaofang@imau.edu.cn (X.-F.Y.); nmgaojulin@163.com (J.-L.G.); 2979187605@qq.com (L,L); madaling@sina.com (D.-l.M.); bthsp88@163.com (S.-p.H.)
*Correspondence: nmyuxiaofang75@imau.edu.cn (X.-F.Y.);nmgaojulin@163.com (J.L.G.)
Tel.: +86-136-7482-7018

Abstract: Grain filling is the key stage for achieving high grain yield. Subsoiling tillage has been widely used as a conservation tillage method in the maize planting region of China. This study was conducted to explore the effects of subsoiling on the grain filling characteristics of maize varieties of different eras. Five typical maize varieties from different eras (1970s, 1980s, 1990s, 2000s and 2010s) were used as trial materials with two tillage modalities: rotation tillage and subsoiling tillage. The characteristic parameters and rate parameters of grain filling were compared and analyzed using the selected tillage modalities. The results showed that the grain filling parameters of the 2010s variety were better than those of the other varieties, and these differences mainly manifested in the filling rate parameters of the rapidly increasing and slowly increasing periods. In comparison with rotation tillage, subsoiling improved the maximum grain filling rate and the grain growth during the period of the maximum grain filling rate to different degrees. In addition, subsoiling delayed the appearance time of the maximum grain filling rate, extended the grain filling duration, and improved the mean filling rate. These differences are major reasons for the significant increase in 100-kernel dry weight at harvest for subsoiling in comparison with rotation tillage. Moreover, subsoiling enhanced the filling rate parameters during the rapidly increasing and slowly increasing periods. The filling stage filling duration and filling rate of maize varieties of different eras showed different responses to subsoiling. For example, the grain filling rate parameters of the 2010s variety during the rapidly increasing period were more sensitive to subsoiling in comparison with those of the other varieties.

Key words: spring maize; subsoiling tillage; grain filling

1.Introduction

Analysis of reports about maize high yield records in China and elsewhere show that increasing maize yield depends on sufficient water and fertilizer conditions, varieties with high yield and density tolerance, high planting density and reasonable cultivation measures[1-2]. Therefore, in the context of the rigid demand for maize grain yield, the reduction of cultivated land area and aggravation of water resource shortages in China, soil fertility improvement, maize variety improvement and innovative cultivation techniques have become effective ways to optimize maize yield per unit area.

It is inevitable that increasing plant density leads to decreased grain yield. In addition, the advantages and disadvantages of topsoil structure further affect the population capacity[3]. A tillage layer with good structure can alleviate the adverse effects of increased density, and practices that optimize this structure are key measures for optimizing maize yield in China. As a conservation tillage measure, subsoiling can effectively improve soil physical and chemical properties, enhance plant self-regulation ability, alleviate the cluster effect of densification, effectively stabilize population yield and realize densification and yield improvement[4-5].

Previous work has shown that grain filling is an important physiological process that determines the yield and quality of maize grain[6-7]. Therefore, by matching appropriate tillage practices[8-9], varieties[10-11], planting density[12-13] and management measures[14], as well as constructing a reasonable group structure to realize full utilization of light, heat, water and fertilizer resources, good filling conditions can be established to achieve coordination of ear number, ear grain number and grain weight, which finally increase the maize yield per unit area.

Studies have shown that subsoiling promoted maize root penetration, increased the photosynthetic rate and delayed leaf senescence, which increased planting density and maize yield[15-17]. However, few studies have assessed the effects of subsoiling on maize grain filling characteristics. Therefore, using maize varieties from different eras as experimental materials, the aim of this study was to analyze the effects of subsoiling on grain filling characteristics to provide a basis for further exploration of the mechanisms underlying increases in planting density and maize yield.

2. Materials and methods

2.1 Trials and measurements

Field experiment were carried out at the Tumoteyou Qi Experimental Station of the Inner Mongolia Agricultural University (40°33′ N, 110°31′ E) during 2018 and 2019. The soil type was sandy loam, and the 0-30 cm soil layer contained 22.27 g·kg^{-1} of organic matter, 103.75 mg·kg^{-1} available nitrogen, 15.76mg·kg^{-1} available phosphorus, and 219.60 mg·kg^{-1} available potassium (pH 8.23). The main meteorological factors during the maize growth period are given in Fig. 1.

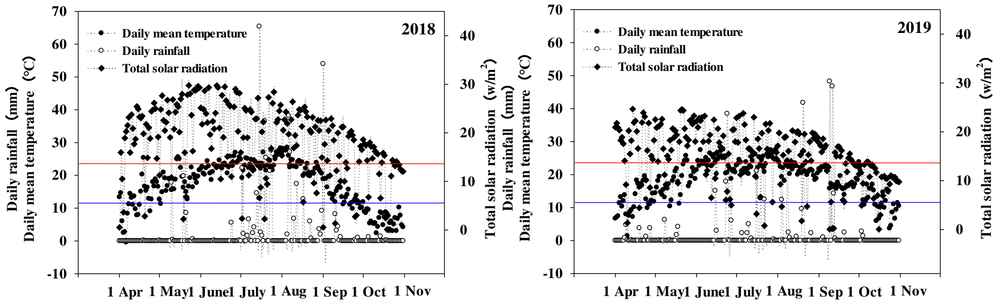

Fig. 1 Main meteorological factors during the growth period in the experimental area

The trial used a two-factor split-plot design (tillage treatment and variety). Tillage treatment was the main plot, and the two tillage practices were subsoiling (SS) with a depth of 35 cm and rotary tillage (RT) with a depth of 15 cm. The main plot contained subplots with each variety: ZD2 (1970s), DY13 (1980s), YD13 (1990s), XY 335 (2000s), and DH618 (2010s). These varieties are sold in the Chinese market and allowed to be purchased as test materials.

The planting density was 75000 plants•hm^{-2}. Interline planting was used with a row spacing of 0.6 m. The plot length and width were each 6 m, and the trial area was 6 × 6 m. The dosages of N, P_2O_5 and K_2O were 465 kg•hm^{-2}, 210 kg•hm^{-2}, and 202.5 kg•hm^{-2}, respectively. P_2O_5 and K_2O were applied as basal fertilizer at seeding. At V6, V12, and R2, N was applied as fertilizer at the ratio of 3:6:1. Subsoiling was achieved with a five-shovel subsoiling plough, and the traction power source was a John Deere 1654 tractor. The plots were irrigated four times during the growth period (seeding stage, V12, R1 and R2) at a rate of 750 m^3/hm^2. The main soil physical characteristic indexes in the trial area are given in Table 1.

Table 1 Main soil physical properties in the test area

Years	Tillage method	VE		R3	
		Soil compaction (Kpa)	Soil moisture content	Soil compaction (Kpa)	Soil moisture content
2018	RT	2194.19	0.17	2675.5	0.15
	SS	1775.23	0.19	2443.14	0.16
2019	RT	2352.46	0.17	1333.41	0.19
	SS	1850.77	0.14	1143.86	0.16

2.2 Measurement

2.2.1 Grain filling characteristics

From 15 days after pollination, samples were collected at 3-day intervals until the end of filling. At each sampling point, three ears were collected per plot, and 100 kernels were collected from the middle of each ear. The kernels were weighed and placed into an oven for 30 min at 105 °C, after which they were dried at 80 °C to a constant weight, and their weight was measured[10]. The collection of experimental material, which complied with relevant institutional, national, and international guidelines and legislation.

A logistic equation[18] was used to fit the grain filling process, calculate grain filling characteristic parameters, and analyze grain filling growth. The logistic equation was calculated as follows:

$$W=A/(1+Be^{-Ct})$$

In the equation above, t is the number of days after flowering (blooming day $t_0=0$), w is the 100-kernel weight after flowering (grain weight on flowering day=w_0), A is the theoretical maximum 100-kernel weight, and B and C are shape parameters. The filling parameters were derived from the first and second derivatives of the equation.

t_1 (the start date of the filling peak period)=(lnB-1.317)/C, corresponding to the grain weight (w_1) at this time: $w_1=A/(1+Be^{-Ct1})$;

t_2 (the end date of the filling peak period)=(lnB+1.317)/C, corresponding to the grain weight (w_2) at this time: $w_2=A/(1+Be^{-Ct2})$;

t_3 (the grain weight reaches 99% after flowering, the effective filling period)=(lnB+4.59512)/C, corresponding to the grain weight (w_3) at this time.

The filling duration of the gradually increasing period was calculated as $T_1=t_1-t_0$. The increase in grain weight during the rapidly increasing period was calculated as $w_1=W_1-W_0$. The mean filling rate of the gradually increasing period was calculated as $v_1=w_1/T_1$.

The filling duration of the rapidly increasing period was calculated as $T_2=t_2-t_1$. The increase in grain weight during the rapidly increasing period was calculated as $w_2=W_2-W_1$. The mean filling rate of the rapidly increasing stage was calculated as $v_2=w_2/T_2$.

The filling duration of the slowly increasing period was calculated as $T_3=t_3-t_2$. The increase in grain weight of the slowly increasing period was calculated as $w_3=W_3-W_2$. The mean filling rate of the slowly increasing stage was calculated as $v_3=w_3/T_3$;

The final grain growth was *A*. Tmax (maximum filling rate time)=lnB/C, Wmax (growth at the maximum filling rate)=A/2, Rmax (the maximum filling rate)=(CWmax)•(1-Wmax/A), *P* (time to complete approximately 90% of total accumulation)=6/C, and vmean (the mean filling rate)=W_3/t_3.

2.2.2 Determination of grain weight

At physiological maturity, ten ears were randomly selected from each plot and air-dried, after which 100 kernels were collected from the middle of each ear and weighed, and this weight was converted to the hundred grain weight with 14% moisture content[19]. The determination of grain weight, which complied with GB/T 5519-2008 national standard.

2.3 Statistical analysis

Statistical analysis was performed using Microsoft Excel 2016 and SAS 9.4 statistical software. The factor analysis was carried out using SPSS 25.0. The filling dynamic fitting was carried out using Curve Expert 1.4 software, and Sigmaplot 12.5 was used to create figures.

3. Results

3.1 Effect of subsoiling on the 100-kernel weight of maize varieties from different eras

Analysis of variance showed that the effects of the different tillage methods, varieties and years on the 100-grain weight were significant at $p<0.01$. The interactions of tillage method*varieties and years*years were also significant, but the effect of tillage method*variety was not significant (Table 2).

Table 2 Variance analysis of the effect of tillage method and variety on the 100-grain weight of maize

Source	DF	Mean Square
Tillage method (M)	1	38.53**
Main area error	2	1.27
Variety (V)	4	181.46**
V*M	4	0.40
Secondary area error	16	0.54
Years	1	7.95**

Note: "*" means significant difference, and "**" means extremely significant difference.

Under the rotation tillage (RT) condition, the mean grain weight of each of the 1970s-1990s varieties was lower than that of the 2010s variety, but the 100-kernel weight of DH618 (2010s) was significantly increased ($P<0.05$). Compared with ZD2, the 100-kernel weight of DY13, YD13, XY335, and DH618 increased by 1.17 g, -1.14 g, 3.62 g and 7.24 g in 2018, respectively, and increased by 1.81 g, 1.99 g, 6.07 g and 10.50 g in 2019, respectively (Fig. 2).

Subsoiling tillage significantly increased the 100-kernel weight of each variety ($P<0.05$). However, there were significant differences in the responses of the varieties to subsoiling. Compared with RT, the mean 100-kernel weight of ZD2, DY3, YD13, XY335 and DH618 for 2018-2019 increased by 1.14 g, 1.35 g, 1.69 g, 1.75 g and 2.09 g, respectively.

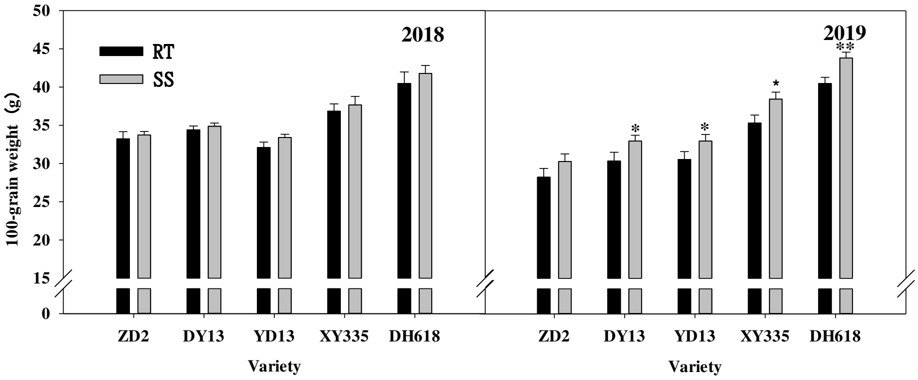

Fig. 2 Effects of deep loosening tillage on the 100-grain weight of different ages maize varieties

3.2 Effect of subsoiling on the kernel dry matter accumulation of maize varieties from different eras

As shown in Fig. 3, from 15 days after silking to physiological maturity, the kernel dry weight increased gradually, and maximum dry weight was achieved at physiological maturity. The kernel dry weight of the tested varieties showed no significant difference from 0-45 d after flowering; however, as the filling process continued, the difference increased progressively. The kernel weight of ZD2, DY13, YD13, XY335, and DH618 increased by 24.66 g, 23.91 g, 23.34 g, 24.07 g and 24.49 g, respectively, from 0-43 d after flowering in 2018, and it increased by 4.74 g, 6.19 g, 5.76 g, 10.52 g and 13.95 g, respectively, from 43-75 d after flowering. In 2019, the kernel weight of ZD2, DY13, YD13, XY335, and DH618 increased by 22.03 g, 22.54 g, 20.91 g, 21.18 g and 21.16 g, respectively, from 0-43 d after flowering, and it increased by 6.89 g, 7.69 g, 9.67 g, 13.19 g and 15.60 g, respectively, from 43-75 d after flowering. These results show that the period from 45-75 d after flowering was the main stage during which significant differences between the kernel dry weight of the old and new varieties manifested.

Compared with RT, subsoiling tillage improved the kernel dry weight of the tested varieties, but the extent of the improvement of kernel dry weight by subsoiling was inconsistent for different filling processes. From 0-43 d after flowering in 2018, the kernel weight of ZD2, DY13, YD13, XY335, and DH618 changed by -0.03 g, -0.64 g, -0.10 g, -0.33 g and -0.58 g, respectively. However, from 43-75 d after flowering, the kernel weight increased by 0.43 g, 1.00 g, 1.01 g, 1.38 g and 1.65 g, respectively. In 2019, the kernel weight of ZD2, DY13, YD13, XY335, and DH618 changed by 0.18 g, -0.10 g, -0.23 g, -0.53 g and -1.13 g, respectively, from 0-43 d after flowering, and the kernel weight increased by 1.84 g, 1.94 g, 1.85 g, 2.38 g and 3.69 g, respectively, from 43-75 d after flowering. These results show that subsoiling mainly increased the kernel dry weight from 43-75 d after maize flowering, and the effect became more obvious as the originating era of the variety became more recent.

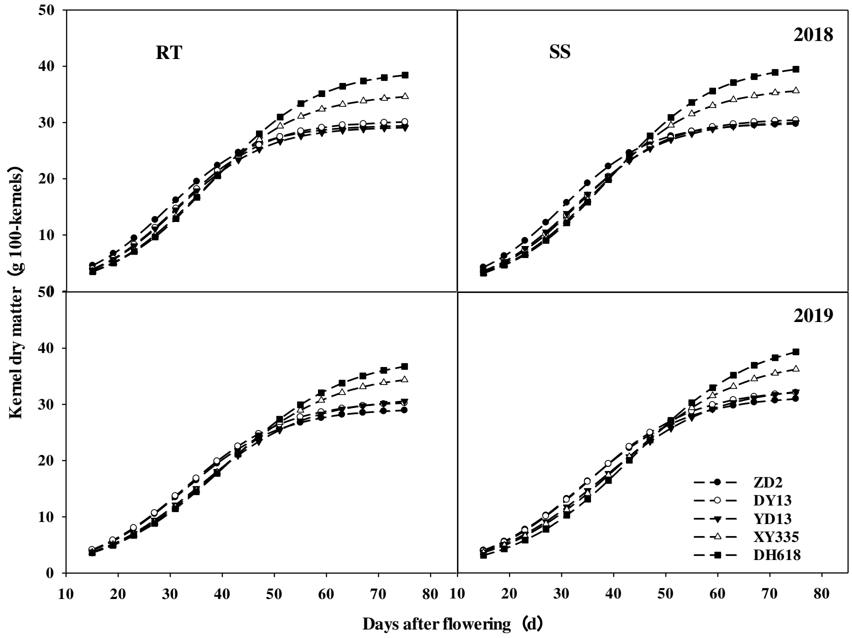

Fig. 3 Effects of deep loosening tillage on the dry weight of 100 grains of maize varieties in different ages

3.3 Effect of subsoiling on the filling characteristic of maize varieties from different eras

3.3.1 Fitting equation for the filling dynamic curves of maize varieties from different eras

The days after flowering (*t*) and weight after flowering (*W*) were used as the independent variable and dependent variable, respectively, in the logistic equation to simulate the grain filling process. According to the functional relationship between dry weight and days after flowering, the grain filling process was divided into three stages: gradually increasing stage, rapidly increasing stage and slowly increasing stage. The parameters of the fitting equation allowed the characteristic parameters of each filling stage to be obtained. The fitting equation determination coefficient (R^2) of the filling process of the tested maize varieties was greater than 0.99, so the logistic equation was determined to fit the grain filling process of maize varieties from different eras (Table 3).

Table 3. Fitting equation of the grain growth curve of each treatment

Year	Tillage method	Variety	Fitting equation	R^2
2018	RT	ZD2	y=29.48/(1+33.92*exp(-0.12x))	0.997
		DY13	y=30.26/(1+39.44*exp(-0.12x))	0.998
		YD13	y=29.24/(1+39.76*exp(-0.12x))	0.998
		XY335	y=35.04/(1+45.05*exp(-0.11x))	0.998
		DH618	y=39.33/(1+48.03*exp(-0.10x))	0.998
	SS	ZD2	y=29.89/(1+37.33*exp(-0.12x))	0.997
		DY13	y=31.40/(1+32.01*exp(-0.10x))	0.997
		YD13	y=30.68/(1+46.74*exp(-0.12x))	0.998
		XY335	y=32.60/(1+34.28*exp(-0.10x))	0.997
		DH618	y=30.20/(1+41.96*exp(-0.12x))	0.998

2019	RT	ZD2	y=29.21/(1+32.02*exp(-0.11x))	0.997
		DY13	y=30.57/(1+31.34*exp(-0.10x))	0.997
		YD13	y=31.13/(1+33.04*exp(-0.10x))	0.998
		XY335	y=35.60/(1+34.97*exp(-0.09x))	0.997
		DH618	y=38.48/(1+37.24*exp(-0.09x))	0.998
	SS	ZD2	y=33.11/(1+32.95*exp(-0.09x))	0.997
		DY13	y=36.23/(1+50.59*exp(-0.11x))	0.999
		YD13	y=38.02/(1+36.39*exp(-0.09x))	0.997
		XY335	y=40.56/(1+53.28*exp(-0.10x))	0.999
		DH618	y=41.89/(1+46.78*exp(-0.09x))	0.998

3.3.2 Effect of subsoiling on the filling characteristic parameters of maize varieties from different eras

As shown in Table 4, the trends of the two-year trial data were basically consistent for filling characteristic parameters under the RT and subsoiling conditions. The filling parameters tended to increase, decrease, and then increase again during variety replacement over the last several decades; YD13 had the lowest values, and DH618 had the highest values. Therefore, the data for 2018 and 2019 were averaged for the following analysis. Under the RT condition, the *A* values of ZD2, DY13, YD13, XY335 and DH618 were 29.35 g, 30.42 g, 30.19 g, 35.32 g and 38.91 g, respectively; the Tmax values were 30.91 d, 32.25 d, 33.44 d, 37.23 d and 39.42 d, respectively; the Wmax values were 14.67 g 100-kernel^{-1}, 15.21 g 100-kernel^{-1}, 15.10 g 100-kernel^{-1}, 17.66 g 100-kernel^{-1} and 19.45 g 100-kernel^{-1}, respectively; the Rmax values were 0.83 g 100-kernel^{-1}d^{-1}, 0.84 g 100-kernel^{-1}d^{-1}, 0.81 g 100-kernel^{-1}d^{-1}, 0.88 g 100-kernel^{-1}d^{-1} and 0.93 g 100-kernel^{-1}d^{-1}, respectively; the *P* values were 53.09 d, 54.45 d, 56.02 d, 60.84 d and 63.31 d, respectively; the Gmean values were 0.41 g 100-kernel^{-1}d^{-1}, 0.41 g 100-kernel^{-1}d^{-1}, 0.39 g 100-kernel^{-1}d^{-1}, 0.42 g 100-kernel^{-1}d^{-1} and 0.44 g 100-kernel^{-1}d^{-1}. During period when the kernel weight was increasing, all of the filling parameters of the modern varieties improved to different degrees.

For the subsoiling condition in comparison with RT, the *A* values of ZD2, DY13, YD13, XY335 and DH618 increased by 4.43%, 4.03%, 5.02%, 5.11%, 5.96%, respectively; the Wmax values increased by 4.46%, 4.01%, 4.84%, 5.12%, and 5.96%, respectively, the Rmax values increased by 1.81%, 1.79%, 1.23%, 2.29%, and 4.86%, respectively, the P values increased by 2.79%, 2.12%, 4.03%, 2.67%, and 1.19%, respectively, the Gmean values increased by 1.13%, 0.29%, 0.55%, 1.56%, and 2.59%, respectively. These results indicate that subsoiling tillage can effectively control the filling characteristic parameters of different ages maize varieties, and the effect was more obvious with varieties that were generated more recently.

Table 4 Response of the grain filling characteristic parameters of maize varieties from different eras to tillage methods

Year	Tillage method	Variety	A (g)	Tmax (d)	Wmax (g 100-kernel^{-1})	Rmax (g 100-kernel^{-1}d^{-1})	P (d)	Gmean (g 100-kernel^{-1}d^{-1})
2018	RT	ZD2	29.48	29.36	14.74	0.88	49.99	0.432
		DY13	30.26	31.47	15.13	0.88	51.39	0.423

		YD13	29.24	31.22	14.62	0.86	50.86	0.413
		XY335	35.04	35.64	17.52	0.94	56.16	0.441
		DH618	39.33	38.07	19.66	1.00	58.99	0.468
		ZD2	29.89	30.08	14.95	0.90	49.86	0.433
		DY13	30.68	33.07	15.34	0.89	51.61	0.418
	SS	YD13	30.20	32.47	15.10	0.87	52.14	0.413
		XY335	36.23	36.96	18.12	0.96	56.52	0.447
		DH618	40.56	39.40	20.28	1.02	59.46	0.473
2019	RT	ZD2	29.21	32.46	14.60	0.78	56.18	0.383
		DY13	30.57	33.02	15.29	0.80	57.51	0.393
		YD13	31.13	35.66	15.57	0.76	61.17	0.374
		XY335	35.60	38.82	17.80	0.81	65.52	0.396
		DH618	38.48	40.77	19.24	0.85	67.62	0.412
	SS	ZD2	31.40	34.24	15.70	0.79	59.27	0.390
		DY13	32.60	35.11	16.30	0.82	59.60	0.400
		YD13	33.20	37.51	16.55	0.77	64.40	0.377
		XY335	38.02	40.98	19.01	0.83	68.41	0.403
		DH618	41.89	44.01	20.94	0.92	68.66	0.429

Note: Tmax is the time when the maximum grouting rate was reached; Wmax is the grain growth at the maximum filling rate; Rmax is the maximum grouting rate; P is the active grouting stage; Gmean is the average grouting rate; A is the ultimate growth rate of the grain.

2.3.3 Path analysis of grain filling characteristic parameters and 100-kernel weight

In order to clarify the direct and indirect relationships between grain filling parameters and maize grain kernel weight, path-coefficient analysis was performed for five filling characteristic parameters and 100-kernel weight (Table 5). Highly significant positive correlations were identified between Tmax, Wmax, *P* and 100-kernel weight ($P<0.01$), and significant positive correlations were identified between Rmax, Gmean and 100-kernel weight ($P<0.05$). The correlation coefficients were ranked as follows:Wmax>Tmax>P>Rmax> Gmean. Wmax and 100-kernel weight had a positive direct correlation, and their correlation coefficient was 0.939. Tmax, Rmax, *P* and Gmean showed positive indirect correlations mainly through Wmax and 100-kernel weight, and their correlation coefficients were 0.866, 0.495, 0.667, and 0.484, respectively. Comprehensive analysis suggests the use of rational cultivation to postpone the appearance of the maximum filling rate during the kernel filling process, while increasing the maximum filling rate to increase kernel growth and achieve the goal of increasing 100-kernel weight.

Table 5 Path analysis of grain filling characteristic parameters

Index	Correlation coefficient	Direct path coefficient	Coupling diameter factor				
			X1	X2	X3	X4	X5
X1	0.893**	0.209		0.866	-0.021	-0.174	0.013
X2	0.976**	0.939	0.193		-0.059	-0.138	0.041
X3	0.540*	-0.113	0.039	0.495		0.040	0.079
X4	0.683**	-0.191	0.191	0.677	0.023		-0.017

X5	0.527*	0.080	0.033	0.484	-0.111	0.041

Note: X1 stands for Tmax, X2 stands for Wmax, X3 stands for Rmax, X4 stands for P, X5 stands for Gmean, and Y stands for 100-grain weight. Tmax is the time when the maximum grouting rate was reached; Wmax is the grain growth at the maximum filling rate; Rmax is the maximum grouting rate; P is the active grouting stage; Gmean is the average grouting rate; A is the ultimate growth rate of the grain.

2.3.4 Effect of subsoiling on the filling rate parameters of maize varieties from different eras

The durations of each stage of maize grain filling were ranked as follows: slowly increasing stage>rapidly increasing stage>gradually increasing stage. The mean filling rates of each stage were ranked as follows: rapidly increasing stage>gradually increasing stage>slowly increasing stage (Table 6). With the exception of the grain filling rate of the gradually increasing stage, the other grain filling rate parameters increased to different degrees during maize variety replacement over the last several decades. Under RT, the two-year mean T1 durations of ZD2, DY13, YD13, XY335, and DH618 were 19.26 d, 20.30 d, 21.14 d, 23.87 d and 25.52 d, respectively, whereas those of T2 were 23.31 d, 23.91 d, 24.59 d, 26.71 d and 27.79 d, respectively; and those of T3 were 29.01 d, 29.75 d, 30.61 d, 33.24 d and 34.59 d. For ZD2, DY13, YD13, XY335, and DH618, the V1 values were 0.33 g 100-kernel^{-1}d^{-1}, 0.32 g 100-kernel^{-1}d^{-1}, 0.31 g 100-kernel^{-1}d^{-1}, 0.32 g 100-kernel^{-1}d^{-1} and 0.32 g 100-kernel-1d^{-1}, whereas their V2 values were 0.73 g 100-kernel^{-1}d^{-1}, 0.74 g 100-kernel^{-1}d^{-1}, 0.72 g 100-kernel^{-1}d^{-1}, 0.77 g 100-kernel^{-1}d^{-1} and 0.82 g 100-kernel^{-1}d^{-1}, respectively, and their V3 values were 0.21 g 100-kernel^{-1}d^{-1}, 0.21 g 100-kernel^{-1}d^{-1}, 0.20 g 100-kernel^{-1}d^{-1}, 0.22 g 100-kernel^{-1}d^{-1} and 0.23 g 100-kernel^{-1}d^{-1}.

Under the subsoiling condition, the grain filling duration was prolonged during different stages of grain filling in comparison with RT, and the increase in filling duration was greatest during the gradually increasing stage. The averaged two-year data revealed that the filling durations of ZD2, DY13, YD13, XY335, and DH618 were prolonged by 4.80%, 7.83%, 5.01%, 5.80% and 8.33%, respectively, during the gradually increasing stage. In addition, subsoiling increased the filling rate of ZD2, DY13, YD13, XY335, and DH618 during the rapidly increasing stage by 2.05%, 2.04%, 0.70%, 2.61%, and 4.29%, respectively, but it had little effect on the filling rate during other stages. These results indicate that subsoiling mainly extended the filling duration during the gradually increasing stage and improved the filling rate during the rapidly increasing stage. Moreover, maize varieties from more recent eras were found to be more sensitive to the effect of subsoiling in comparison with relatively older varieties.

Table 6 Response of grain filling rate parameters of different ages maize varieties to tillage methods

Year	Tillage method	Variety	T1 (d)	V1 (g 100-kernel^{-1}d^{-1})	T2 (d)	V2 (g 100-kernel^{-1}d-^{1})	T3 (d)	V3 (g 100-kernel^{-1}d^{-1})
2018	RT	ZD2	18.39	0.34	21.95	0.78	27.31	0.22
		DY13	20.19	0.32	22.56	0.77	28.08	0.22
		YD13	20.05	0.31	22.33	0.76	27.79	0.21
		XY335	23.31	0.32	24.65	0.82	30.68	0.23
		DH618	25.12	0.33	25.90	0.88	32.23	0.25
	SS	ZD2	19.14	0.33	21.89	0.79	27.24	0.22

		DY13	21.74	0.30	22.66	0.78	28.20	0.22
		YD13	21.03	0.30	22.89	0.76	28.48	0.21
		XY335	24.55	0.31	24.81	0.84	30.88	0.24
		DH618	26.35	0.33	26.10	0.90	32.49	0.25
2019	RT	ZD2	20.13	0.31	24.66	0.68	30.70	0.19
		DY13	20.40	0.32	25.25	0.70	31.42	0.20
		YD13	22.23	0.30	26.85	0.67	33.42	0.19
		XY335	24.43	0.31	28.77	0.71	35.80	0.20
		DH618	25.92	0.31	29.68	0.75	36.94	0.21
	SS	ZD2	21.23	0.31	26.02	0.70	32.38	0.20
		DY13	22.03	0.31	26.17	0.72	32.57	0.20
		YD13	23.37	0.30	28.27	0.68	35.18	0.19
		XY335	25.96	0.31	30.03	0.73	37.37	0.20
		DH618	28.94	0.31	30.14	0.80	37.51	0.22

Note: T1 represents the grain filling duration of the gradually increasing stage, V1 represents the average grain filling rate of the gradually increasing stage, T2 represents the grain filling duration of the rapidly increasing stage, V2 represents the average grain filling rate of the rapidly increasing stage, T3 represents the grain filling duration of the slowly increasing stage, and V3 represents the average grain filling rate of the slowly increasing stage.

3.3.5 Analysis of the grouting rate parameter factor

In order to clarify the internal dependence of the grain filling rate and duration at each stage, factor analysis was performed using the two-year trial data (Table 7). Under RT, the factor load difference of the filling duration was small at each stage (T1=0.96, T2=0.96, T3=0.96), which indicated that the proportion of the filling duration of each stage was nearly identical. Under subsoiling, the factor load difference of the grain filling duration between T1 and T2/T3 was large (T1=0.91, T2=0.97, T3=0.97), which indicated that the effect of subsoiling on the grain filling duration was stronger during the rapidly increasing and slowly increasing stages. In addition, the factor load of the filling rate during the rapidly and slowly increasing stages was higher than that of the gradually increasing stage, which showed that the filling rate during the rapidly and slowly increasing stages contributed more to the mean filling rate in comparison with that of the gradually increasing stage. These results demonstrate that appropriate tillage measures can improve the filling rate during the rapidly increasing and slowly increasing stages, and thus improve the mean filling rate.

Table 7 Parameter factor analysis of grain filling rate

Farming methods	SS		SS	
Index	Y1	Y2	Y1	Y2
T1	0.961	0.249	0.914	0.340
V1	-0.414	0.766	-0.055	0.721
T2	0.958	-0.233	0.970	-0.211
V2	0.021	0.985	-0.001	0.983
T3	0.958	-0.234	0.971	-0.210
V3	0.022	0.992	-0.069	0.971

Note: the extraction method was principal component analysis, Y1 represents the grouting duration, and Y2 represents the average grouting rate. T1 represents the grain filling duration of the gradually increasing stage, V1 represents the average grain filling rate of the gradually increasing stage, T2 represents the grain filling duration of the rapidly increasing stage, V2 represents the average grain filling rate of the rapidly increasing stage, T3 represents the grain filling duration of the slowly increasing stage, and V3 represents the average grain filling rate of the slowly increasing stage.

4. Discussion

Previous studies have shown that the grain weight of maize is mainly determined by the filling rate and filling duration. Therefore, improving the grain filling rate and ensuring that grain filling is maintained for an appropriate duration could increase grain weight and yield[20-23]. Fang et al.[24] showed that the grain filling rate determined dry matter accumulation and affected yield, and they showed that the implementation of a reasonable planting method could improve the grain filling rate. Gasura et al.[25] reported that extending the active grain filling period and increasing the mean filling rate increased maize yield. Daynard et al.[26] found that prolonging the filling duration increased the 100-kernel dry weight of maize. On the basis of previous studies, the present study further explored the characteristics of maize grain filling and revealed that improving the mean filling rate and delaying the occurrence of the maximum filling rate led to increased grain growth during the period of the maximum filling rate. In addition, we found that the filling rates of the rapidly increasing and slowly increasing stages primarily determined the mean filling rate, whereas that of the gradually increasing stage had a weaker influence on the mean filling rate. Therefore, during the period from 20 days after silking to physiological maturity, which encompasses the rapidly increasing and slowly increasing stages of grain filling, the level of plant material accumulation was strongly correlated with the mean filling rate, and implementing practices that maximize plant dry matter accumulation will be beneficial to the further improvement of grain weight.

Conservation agriculture, such as the use of no tillage, less tillage, and straw mulch, has been an important strategy for the sustainable development of worldwide agriculture in the past few decades, because conservation agriculture can improve soil properties while increasing income and crop yields[27]. Farming methods are a key factor affecting soil systems in China, where soil management and seeding are mainly performed using small tractors, and a significant portion of farmland is subjected to methods involving less tillage or no tillage, which increase the surface soil bulk density and osmotic resistance, which have deleterious effects on crop growth[28-30]. Previous studies demonstrated that the use of optimized farming methods increased crop yield[31-32]. For example, subsoiling increased yield by improving the 100-kernel weight of maize[33]. Zhai et al.[34] showed that subsoiling increased the maximum and mean kernel filling rates, which significantly increased the maximum kernel weight at harvest. Cai et al.[35] et al. showed that subsoiling increased kernel weight, improved plant resistance to environmental stresses, and increased yield. In this study, we further analyzed the filling characteristics of maize varieties from different eras using subsoiling, and we showed that, compared with conventional rotation, subsoiling significantly improved kernel weight by increasing the maximum filling rate and prolonging the duration of the maximum grain filling rate. The beneficial effects of subsoiling on filling characteristics were likely observed because subsoiling tillage the bottom of the ploughed stratum, increased the topsoil depth, improved water storage and moisture conservation, promoted root growth and development[36-37], maintained a high leaf area index and photosynthetic rate after anthesis, and slowed the subsequent decrease in photosynthetic rate. Therefore, the implementation of subsoiling tillage was beneficial for maize because it led to the production of more photosynthetic products[38], thus increasing the grain filling rate and kernel weight.

4 Conclusion

During variety replacement over the last several decades, kernel weight was significantly increased, while kernel growth during the period of the maximum kernel filling rate was improved, the durations of the active filling period and maximum filling rate were prolonged, and the maximum filling rate and mean filling rate were increased. Compared with the other trial varieties, the 2010s variety had a longer gradually increasing period, and its filling rates during the rapidly increasing and slowly increasing period were improved to different degrees. Subsoiling tillage increased the maximum grain filling rate, postponed the occurrence of the maximum filling rate, prolonged the duration of the gradually increasing period, improved the filling rates of the rapidly increasing period and slowly increasing period, and increased grain weight. The filling rate of the rapidly increasing period of the 2010s variety was more sensitive to subsoiling tillage in comparison with the other trial varieties.

Author Contributions: Performed the experiments: L-q.W., J-l.G. and S-p.H. Analyzed the data: L-q.W., D-l.M. and X-f.Y.. Revised the manuscript critically for important intellectual content: X-f.Y., J-l.G. and D-l.M. ,Wrote the paper: L-q.W, L.L. and X-f.Y. .

Funding:

Acknowledgments: This study was supported by the National Natural Science Foundation of China (grant no. 31560360), the Science & Technology Innovation Projects for High Yield and Efficiency of Grain (grant no. 2017YFD0300804), the National Maize Industrial Technology Systems (grant no. CARS-02-50), and the Crop Science Observation & Experiment Station in Loess Plateau of North China, Ministry of Agriculture, P. R. of China (grant no. 25204120).

Conflicts of Interest: Page: 12
The authors declare no conflicts of interest.

References

1. Hai-Peng H, Wei M A, Noor M A, et al. Quantitative design of yield components to simulate yield formation for maize in China[J]. Journal of Integrative Agriculture, 2020, 019(003):P.668-679.
2. Li Shaokun, Wang Keru, Yang Xiaoxia, Han Dongsheng, Wang Yuhua, Xie Ruizhi, Hou Peng, Ming Bo. Technology and Benefit Analysis of High Yield Record Field in Maize.Crops,2017(06):1-6. (in Chinese with English abstract)
3. Shulan Wang, Hao Wang, Muhammad Bilal Hafeez, et al. No-tillage and subsoiling increased maize yields and soil water storage under varied rainfall distribution: A 9-year site-specific study in a semi-arid environment. 2020, 255.
4. Yu Xiaofang, Sun Hongli, Gao Julin, Wang Zhigang, Yang Hengshan, Zhang Ruifu, Hu Shuping, Sun Jiying. Mechanism behind densification and yield increase of spring maize with different density-tolerance regulated by subsoiling [J]. Transactions of the Chinese Society of Agricultural Engineering,2019,35(13):35-46. (in Chinese with English abstract)

5. Jr J L P , Aase J K . Water Infiltration and Storage affected by Subsoiling and Subsequent Tillage[J]. Soilence Society of America Journal, 2003, 67(3):859-866.
6. Li Q , Du L , Feng D , et al. Grain-filling characteristics and yield differences of maize cultivars with contrasting nitrogen efficiencies[J]. The Crop Journal, 2020.
7. Butts-Wilmsmeyer C , Seebauer J , Singleton L , et al. Weather During Key Growth Stages Explains Grain Quality and Yield of Maize[J]. Agronomy, 2019, 9(1).
8. Simi M , Dragievi V , Drini S M , et al. The Contribution of Soil Tillage and Nitrogen Rate to the Quality of Maize Grain[J]. Agronomy, 2020, 10(7):976.
9. Zhou B , Sun X , Wang D , et al. Integrated agronomic practice increases maize grain yield and nitrogen use efficiency under various soil fertility conditions[J]. The Crop Journal, 2019.
10. Li Q , Du L , Feng D , et al. Grain-filling characteristics and yield differences of maize cultivars with contrasting nitrogen efficiencies[J]. The Crop Journal, 2020.
11. Li-Xia S , Yan-Kai H , Ting L I . Top-grain filling characteristics at an early stage of maize(Zea mays L.) with different nitrogen use efficiencies[J]. Journal of Integrative Agriculture, 2017, 16(003):626-639.
12. Jia Q , Sun L , Mou H , et al. Effects of planting patterns and sowing densities on grain-filling, radiation use efficiency and yield of maize (Zea mays L.) in semi-arid regions[J]. Agricultural Water Management, 2018:287-298.
13. Wei S , Wang X , Li G , et al. Plant Density and Nitrogen Supply Affect the Grain-Filling Parameters of Maize Kernels Located in Different Ear Positions[J]. other, 2019, 10. 2019, 10:180.
14. Ning-Ning Y U , Zhang J W , Liu P , et al. Integrated agronomic practices management improved grain formation and regulated endogenous hormone balance in summer maize (Zea mays L.)[J]. Journal of Integrative Agriculture, 2020, 19(7):1768-1776.
15. Xiaofang Yu,Qi Zhang,Julin Gao,Zhigang Wang,Qinggeer Borjigin,Shuping Hu,Baolin Zhang,Daling Ma. Planting Density Tolerance of High-Yielding Maize and the Mechanisms Underlying Yield Improvement with Subsoiling and Increased Planting Density[J]. Agronomy,2019,9(7).
16. Wu W , Wang S , Zhang L , et al. Subsoiling Improves the Photosynthetic Characteristics of Leaves and Water Use Efficiency of Rainfed Summer Maize in the Southern Huang-Huai-Hai Plain of China[J]. Agronomy, 2020, 10(4):465.
17. Amato, Mariana. Spatial Distribution of Roots and Water Uptake of Maize (Zea mays L.) as Affected by Soil Structure[J]. Crop Science, 2002.
18. Xiaohui Wang, Lei Zhang, Shuangli Liu, Yujun Cao, Wenwen Wei, Chunguang Liu, Yongjun Wang, Shaofeng Bian, Lichun Wang. Grain Filling Characteristics of Maize Hybrids Differing in Maturities [J]. Scientia Agricultura Sinica,2014,47(18):3557-3565. (in Chinese with English abstract)
19. GB/T 5519-2008, Determination of 1000-grain weight of cereals and legumes [S], China, National Food and Strategic Reserves Administration, 2012-10-11.
20. Youjia Chen, Gerrit Hoogenboom, Yuntao Ma, et al. Maize kernel growth at different floret positions of the ear. 2013, 149:177-186.
21. Borrás, Lucas, Zinselmeier C , Senior M L , et al. Characterization of Grain-Filling Patterns in Diverse Maize Germplasm[J]. Crop Science, 2009, 49(3).
22. Sadras V O , Egli D B . Seed Size Variation in Grain Crops: Allometric Relationships between Rate and Duration of Seed Growth[J]. Crop Science, 2008, 48(2):408.
23. Johnson D R , Tanner J W . Calculation of the Rate and Duration of Grain Filling in Corn (Zea mays

L.)1[J]. Crop ence, 1972, 12(4).

24. Fang H , Gu X , Jiang T , et al. An optimized model for simulating grain-filling of maize and regulating nitrogen application rates under different film mulching and nitrogen fertilizer regimes on the Loess Plateau, China[J]. Soil and Tillage Research, 199.
25. Gasura E , Setimela P , Edema R , et al. Exploiting Grain-Filling Rate and Effective Grain-Filling Duration to Improve Grain Yield of Early-Maturing Maize[J]. Crop ence, 2013, 53(6).
26. Daynard T B, Tanner J W, Duncan W G.Duration of the grain filling period and its relation to grain yield in corn, Zea mays L.[J].Crop Science, 1971, 11 (1) :45-48.
27. Gathala M K , Timsina J , Islam M S , et al. Conservation agriculture based tillage and crop establishment options can maintain farmers' yields and increase profits in South Asia's rice–maize systems: Evidence from Bangladesh[J]. Field Crops Research, 2015, 172:85-98.
28. Liu X B , Zhang X Y , Wang Y X , et al. Soil degradation: A problem threatening the sustainable development of agriculture in Northeast China[J]. Plant Soil & Environment, 2010, 56(2):87-97.
29. Zhang X , Pei D , Chen S . Root growth and soil water utilization of winter wheat in the North China Plain[J]. Hydrological Processes, 2010, 18(12):-.
30. ?íp, Václav, Vavera R , Chrpová, Jana, et al. Winter wheat yield and quality related to tillage practice, input level and environmental conditions[J]. Soil & Tillage Research, 2013, 132:77-85.
31. Piao L , Qi H , Li C , et al. Optimized tillage practices and row spacing to improve grain yield and matter transport efficiency in intensive spring maize[J]. Field Crops Research, 2016, 198:258-268.
32. Shi Y , Yu Z , Man J , et al. Tillage practices affect dry matter accumulation and grain yield in winter wheat in the North China Plain[J]. Soil and Tillage Research, 2016.
33. Zhang Ruifu, Yang Hengshan, Gao Julin, Zhang Yuqin, Wang Zhigang, Fan Xiuyan, Bi Wenbo. Effect of subsoiling on root morphological and physiological characteristics of spring maize[J]. Transactions of the Chinese Society of Agricultural Engineering,2015,31(05):78-84. (in Chinese with English abstract)
34. Lichao Zhai,Ping Xu,Zhengbin Zhang, et al.Effects of deep vertical rotary tillage on dry matter accumulation and grain yield of summer maize in the Huang-Huai-Hai Plain of China[J]. Soil & Tillage Research,2017,170:167-174.
35. Hongguang Cai, Wei Ma, Xiuzhi Zhang, et al. Effect of subsoil tillage depth on nutrient accumulation, root distribution, and grain yield in spring maize. 2014, 2(5):297-307.
36. Bian D , Jia G , Cai L , et al. Effects of tillage practices on root characteristics and root lodging resistance of maize[J]. Field Crops Research, 2016, 185:89-96.
37. Dahai Guan, Mahdi M. Al-Kaisi, Yushi Zhang, et al. Tillage practices affect biomass and grain yield through regulating root growth, root-bleeding sap and nutrients uptake in summer maize. 2014, 157:89-97.
38. Zhou Baoyuan, Sun Xuefang, Ding Zaisong, Ma Wei, Zhao Ming. Effect of Tillage Practice and Fertilization on Dry Matter Accumulation and Grain Yield of Summer Maize[J]. Scientia Agricultura Sinica,2017,50(11):2129-2140. (in Chinese with English abstract)

Figures

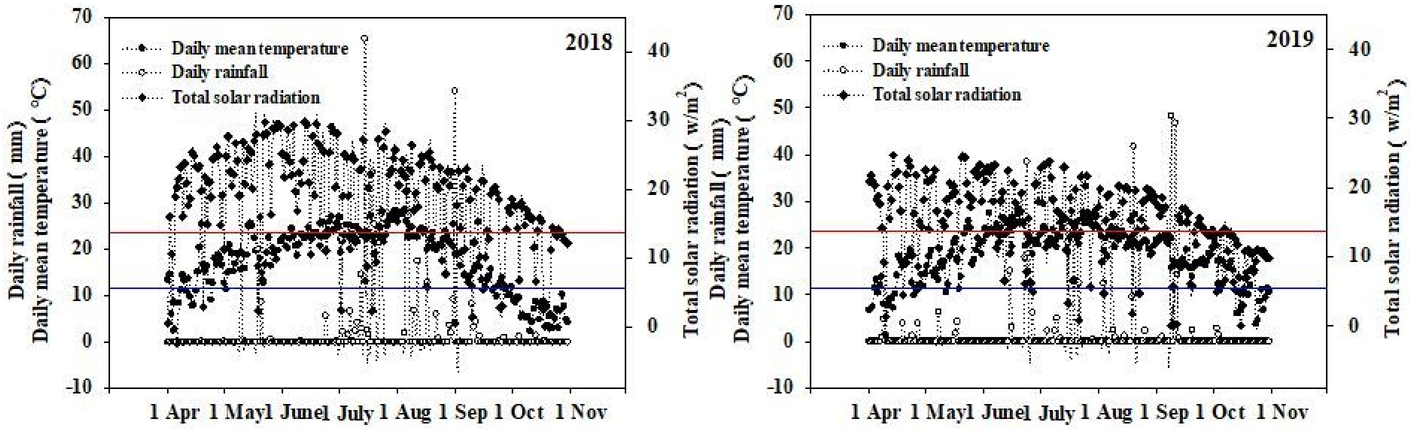

Figure 1

Main meteorological factors during the growth period in the experimental area

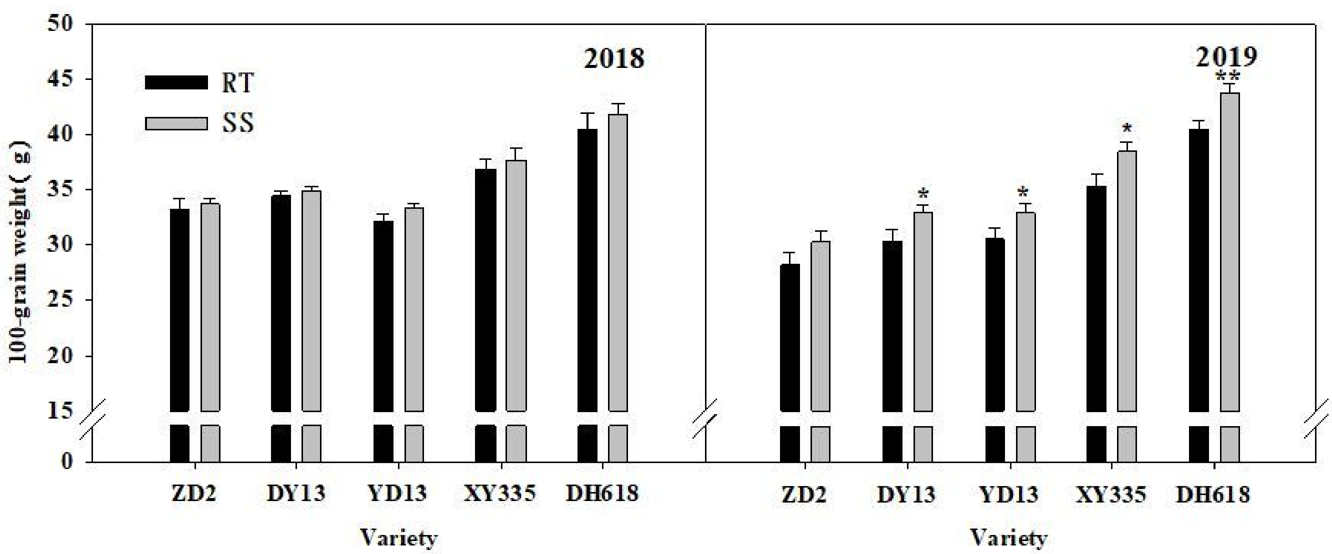

Figure 2

Effects of deep loosening tillage on the 100-grain weight of different ages maize varieties 3.2 Effect of subsoiling on the kernel dry matter accumulation of maize varieties from different eras

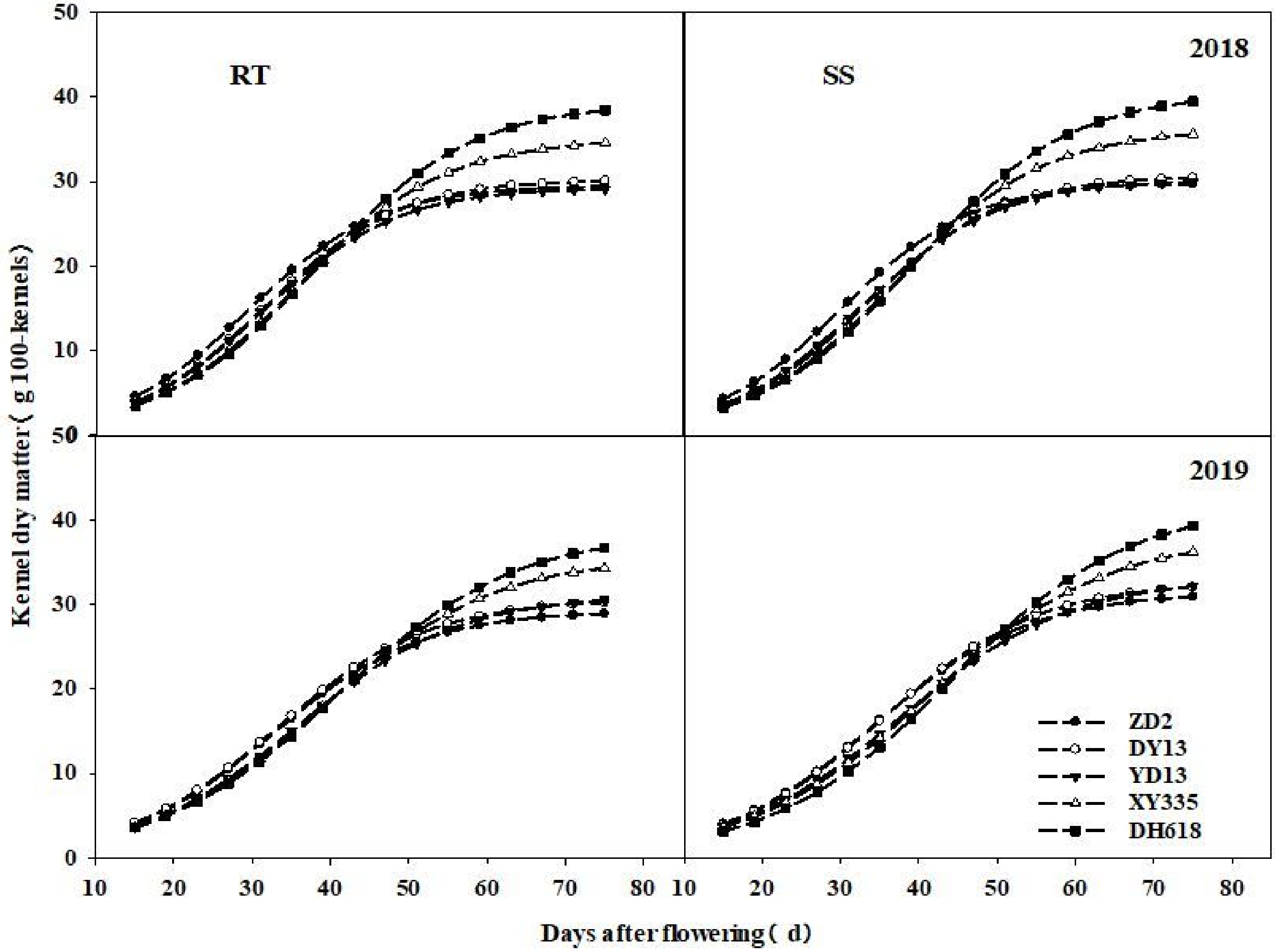

Figure 3

Effects of deep loosening tillage on the dry weight of 100 grains of maize varieties in different ages