

Poor post-silking kernel development limits summer maize yield in the North China Plain

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ABSTRACT: Winter wheat (*Triticum aestivum*)/summer maize (*Zea mays*) rotation is a major system in the North China Plain. The wheat yield target was achieved recently, whereas the maize yield has been static since the 2000s, even with high density planting and fertilizer input. This study analyses the factors limiting maize growth and yield. Maize yields from eight field trials (2006–2011) were classified into five levels: low yield (< 8.25), farmer yield (8.25–9.75), experimental yield (9.75–11.25), record high yield (11.25–12.75), and target yield (> 12.75) t/ha. Shoot dry weight, nitrogen accumulation, and leaf area index at critical stages, yield, and yield components were measured. Grain yield fluctuated from 6.4–13.8 t/ha (10.1 t/ha on average). Insufficient kernel number per ear and low kernel weight limited further yield improvement. Shoot dry weight, leaf area index, and shoot N-accumulation before silking did not vary among the different yield levels, whereas after silking these parameters were significantly larger at high yield levels. It can be concluded that low kernel number per ear across yield levels was related to source limitation pre-silking. Additionally, low kernel weight was due to poor post-silking dry matter production. However, the potential of yield increment through increasing source size was limited under the current system. Strategies to enhance post-silking leaf and root function shall therefore be considered to improve post-silking dry matter production and transportation under a high density and high nitrogen input system.

KEYWORDS: leaf area index, dry matter, nitrogen, root growth

INTRODUCTION

Winter wheat (*Triticum aestivum*) and summer maize (*Zea mays*) are two major crops within a rotation system in North China Plain (NCP), and account for about 60% of arable land (Chinese Statistics Year Book, 2012). There are seven provinces (cities) involved in this area¹ where summer maize is traditionally sowed one week before or directly after the harvesting of winter wheat depending on meteorological conditions at different locations within NCP. Annual regional grain yield (winter wheat plus summer maize) ranges from 11–13 t/ha^{2,3} with a tendency of a tremendous yield increase since the 1960s but relatively stable yield after mid-1990s in NCP⁴.

According to the results of modelling, potential yield of winter wheat can reach 9.75 t/ha⁵, and

13–15 t/ha for summer maize⁶. In recent years, the experimental grain yield of winter wheat is stabilized at 9–9.5 t/ha⁷, and that of summer maize is around 9–11.5 t/ha^{8,9}. Since winter wheat usually consumes large amount of water, the environmental cost for yield improving would become higher and higher under current yield level. Thus more attention is paid on the improvement of summer maize yield due to its high yield potential.

In the NCP, plant density increased to as high as 9–12 plants per m² and was applied for several varieties under experimental condition, while the increment of maize yield reached plateau at 10–11 t/ha¹⁰, implying little contribution to yield improvement through the increase of density with current varieties. Additionally, plant growth regulator was also applied to summer maize in order to increase the density resistance without obtaining

Table 1 Metrological condition of maize growing season in Heilonggang River Valley from 1996–2011.

	June		July		August		September		October
	01–15	16–30	01–15	16–31	01–15	16–31	01–15	16–30	01–15
Average daily temperature (°C)	25.1	26.6	27.5	27.5	27.0	24.7	22.7	20.0	16.4
Average daily temperature range (°C)	12.1	10.8	9.8	8.4	8.4	8.9	10.1	10.7	10.7
Cumulative precipitation (mm)	19.3	56.2	69.6	86.5	67.3	52.4	24.0	18.1	29.4
Average daily relative humidity (%)	54.6	64.1	69.5	76.6	77.7	77.2	72.4	68.4	66.4
Average daily sunshine hours (h)	8.9	7.6	7.5	6.5	6.8	7.1	7.4	7.1	6.7

Table 2 Soil chemical properties of the experimental field from 2006–2011.

Soil depth (cm)	Organic matter (g/kg)	Total N (g/kg)	Available N (mg/kg)	Olsen-P (mg/kg)	Exchangeable K (mg/kg)	Bulk density (g/cm ³)
0–20	10.4 ± 1.7 [†]	0.9 ± 0.2	67 ± 14	24 ± 14	131 ± 29	1.51
20–40	5.3 ± 1.1	0.4 ± 0.1	34.2 ± 7.8	3.4 ± 1.2	94 ± 19	1.48

[†] Standard deviation.

a significant yield improvement¹¹. Furthermore, many experiments on nitrogen fertilization regimes, i.e., fertilizer type, timing, and doses, were conducted^{9,12}. A suitable N application rate was determined and N supply at three-leaf and twelve-leaf stages was essential to achieve high efficiency and yield^{8,13}. These efforts however were unable to achieve a stable yield higher than 11.5 t/ha until now. It is urgently needed to understand the summer maize growing system and to break the bottlenecks of yield improvements in NCP.

We designed eight field trials in order to: (1) understand maize growing and nitrogen accumulation character under different yield levels, (2) analyse the constraints to yield improvement, and (3) suggest the possible solutions to break the bottlenecks on yield improvement.

MATERIALS AND METHODS

Site description and data sources

Field experiments were conducted from 2006–2011 at Wuqiao Experimental Station of China Agricultural University (37° 41' N, 116° 37' E, 18 m asl), Hebei Province, China. This area has a typical semi-humid continental monsoon climate. Meteorological data of maize growing season (1996–2011) were obtained from China Meteorological Data Sharing Service System (www.cdc.cma.gov.cn) and shown in Table 1. Samples from nine points were taken with a shape of 'S' across the field at the on-set of each experiment. The soil texture of the experimental site was light loam with pH value greater than 8. The chemical properties at 0–20 cm and 20–40 cm soil depth were measured and are presented in Table 2.

Data used in this paper were based on eight field experiments conducted on station from 2006–2011. ZD958, a commercially available and widely used cultivar, was applied under different plant densities and nitrogen fertilization rates in all experimental years (Table 3). Within each field experiment, a complete randomized block design was applied with three or four replicates. In relation to different plant densities and nitrogen fertilization rates, yields were classified into five levels for growth analysis: (1) low yield, grain yields (14% water content) less than regional average yield (< 8.25 t/ha, *n* = 14); (2) farmer yield, regional average yield (8.25–9.75 t/ha, *n* = 38); (3) experimental yield^{12,13}, average yield of scientific experiments in this region (9.75–11.25 t/ha, *n* = 54); (4) record high yield¹⁴, the highest yield in this region (11.25–12.75 t/ha, *n* = 21); and (5) target yield¹⁰, modelled grain yields (> 12.75 t/ha, *n* = 3).

Field managements

Summer maize was directly seeded after the harvest of winter wheat without tillage. Maize seeds were sowed on 14–20 June and harvested from 27 September to 10 October according to the maturity. Irrigation was conducted only once before sowing or no irrigation during the entire growing period according to soil moisture at sowing. P and K fertilizers were applied as the basal fertilizers, while N fertilizer was applied as the basal and top-dressing fertilizer. Detailed field managements are presented in Table 3. Propisochlor (2-chloro-6'-ethyl-N-isopropoxymethylacet-*o*-toluidide) and atrazine

Table 3 Field managements of nine experiments conducted in Wuqiao experimental station of China Agricultural University from 2006–2011.

Year	Experiment code	Plant density (plants/m ²)	Plot size (m ²)	Sowing date	Harvest date	Irrigation (mm)	N (kg/ha)	P ₂ O ₅ (kg/ha)	K ₂ O (kg/ha)
2006	1	8.25, 9.75, 11.25	42	17 June	3 October	60	0, 90, 180, 270 [†]	103.5	112.5
2007	2	8.25	42	16 June	27 September	60	0, 90, 180, 270 [†]	103.5	112.5
2007	3	8.25	50.4	17 June	5 October	75	75, 120, 300 [‡]	105	120
2007	4	8.25	50.4	17 June	5 October	75	75, 120, 300 [‡]	105	120
2008	5	8.25	54	11 June	2 October	150	0, 120, 150,	90	90
2009	6	8.25	54	14 June	2 October	150	180, 240 [§]	90	90
2010	7	6, 7.5, 9	57.6	20 June	17 October	0	0, 180, 270 [¶]	105	120
2011	8	6, 7.5, 9	43.2	15 June	10 October	0	0, 180, 270 [¶]	105	120

[†] N applied with a ratio of 1:4 as basal and top-dressing at 12 collars stage.

[‡] N applied with a ratio of 1:2 at 3 collars and 12 collars stage, respectively.

[§] N applied at 0, 30, 60, and 120 kg/ha at 3 collars stage, and 120 kg/ha at 12 collars stage for all treatments.

[¶] N applied at 30 and 120 kg/ha at 3 collars stage for both N treatments, and 120 and 30 kg/ha at 12 collars stage respective silking stage for all. N applied with a ratio of 1:1 as basal and top-dressing at 12 collars stage.

(6-chloro-*N*²-ethyl-*N*⁴-isopropyl-1,3,5-triazine-2,4-diamine) were applied directly after sowing to suppress the emergence of weed. Cyhalothrin {(RS)- α -cyano-3-phenoxybenzyl-(1RS,3RS)-3[(Z)-2-chloro-3,3,3-trifluoropropenyl]-2,2-dimethylcyclopanecarboxylate} were applied to control pests when necessary.

Plant sampling and measurements

Maize developmental stages were classified as six collars (V6), nine collars (V9), twelve collars (V12), silking (R1), blister (R2), and physiological maturity stage (R6). At V6, V9, V12, R1 and R6 stages, plant samples were collected from the sampling area. A fixed and non-disturbed area (final harvest area) within each plot was determined when experiments were settled up, which were only used for measuring grain yield and yield components. On each sampling campaign, three or four plants were harvested around the final harvest area of each plot. Plants aboveground parts were separated into green leaves, stems (including leaf sheaths and necrotic leaves), and ears (when present). Leaf area was determined by measuring length and width of leaves. Leaf area index (LAI) was calculated as leaf area per unit of land area (LA = length \times width \times 0.75). Shoot dry matter was determined after oven-drying at 80 °C to a constant weight. Dry plant samples were ground and digested by H₂SO₄-H₂O₂, and the N concentration was measured by Kjeldahl method. At physiological maturity, the final harvest area (9.6 m²) was harvested by hands to determine the maize yields (14% water content). Ten ears were randomized picked within the final harvest area to measure kernel number per ear and 1000-kernel weight.

Data calculation and statistical analysis

Each plot of experiment 1 to experiment 8 represented one data point, and thus 130 data points totally. These 130 data points were classified to five levels according to their final yield, and thus growth parameters and their relationships with yield were analysed among yield levels. ANOVA was performed with general linear model procedure of the Statistical Analysis System, version 9.0 (SAS Institute Inc., 2002). Correlations between parameters were checked according to Pearson correlation in SAS.

RESULTS

Generally, the grain yield on station ranged from 6.4–13.8 t/ha with an average yield of 10.1 t/ha, and ear numbers ranged from 14.5–30.3 \times 10³ per ha, kernel number per ear ranged from 273–574, and 1000-kernel weight ranged from 227–356 g over six experimental years. The coefficients of variation for these averages were 10.8–17% (Table 4). With the increase of yield levels, ear number per ha was similar at around 80 000, while kernel number per ear increased, and significant difference occurred between high yield levels (> 11.25 t/ha) and low yield levels (< 11.25 t/ha). On the contrary, 1000-kernel weight at low yields was greater than at high yield.

Grain dry weight increased sequentially with the increase of yield levels, while straw dry weight at harvest showed no difference among yield levels (Table 5). Moreover, grain N accumulation significantly increased with the increase of yield level, while straw N accumulation only increased slightly with no statistic difference among yield levels. Moreover, the higher the grain yield, the

Table 4 Number of observations (no. obs.; amount of data points), yield levels, and coefficient of variation (CV) of grain yield (14% water content) and yield components of summer maize in Wuqiao experimental station of China Agricultural University from 2006–2011.

No. obs. (n)	Grain yield level (t/ha)	Average grain yield (t/ha)	Ear number ($\times 10^3$ /ha)	Kernel number (No./ear)	1000-kernel weight (g)
14	< 8.25	7.5 ^e	81.8 ^a	389 ^b	292 ^a
38	8.25–9.75	9.2 ^d	78.4 ^a	398 ^b	282 ^{ab}
54	9.75–11.25	10.5 ^c	79.4 ^a	385 ^b	285 ^{ab}
21	11.25–12.75	11.9 ^b	83.9 ^a	494 ^a	258 ^b
3	> 12.75	13.6 ^a	78.8 ^a	423 ^a	256 ^b
130	6.4–13.8	10.1	145.4–30.3	273–574	227–356
CV (%)	14.1	—	17.0	15.5	10.8

Figures within each column followed by the same letters are not significantly different, $p < 0.05$.

Table 5 Grain dry weight (GDrW), straw dry weight (SDrW), grain N accumulation (GN), straw N accumulation (SN), harvest index (HI), and nitrogen harvest index (NHI) of summer maize in Wuqiao experimental station of China Agricultural University from 2006–2011.

Yield level (t/ha)	GDrW (t/ha)	SDrW (t/ha)	GN (kg/ha)	SN (kg/ha)	HI	NHI
< 8.25	6.5 ^e	9.5 ^a	93.1 ^d	61.5 ^a	0.41 ^d	0.60 ^a
8.25–9.75	7.9 ^d	9.3 ^a	112.0 ^{cd}	63.5 ^a	0.46 ^c	0.64 ^a
9.75–11.25	9.1 ^c	9.7 ^a	125.7 ^{bc}	74.0 ^a	0.48 ^{bc}	0.63 ^a
11.25–12.75	10.3 ^b	9.3 ^a	138.2 ^b	80.9 ^a	0.53 ^{ab}	0.63 ^a
> 12.75	11.7 ^a	10.2 ^a	170.2 ^a	77.7 ^a	0.54 ^a	0.69 ^a

Figures within each column followed by the same letters are not significantly different, $p = 0.05$.

greater the harvest index, but nitrogen harvest index values were similar under different yield levels.

Shoot dry weight, leaf area index, and shoot N accumulation showed no statistical difference among yield levels at 6 collars stage (V6, data not shown), 9 collars stage (V9), and silking stage (R1) (Fig. 1). However, significant difference was observed at physiological maturity (R6), i.e., with the increase of yield levels, shoot dry matter, leaf area index, and shoot N accumulation all increased significantly during silking to physiological maturity (Fig. 1).

Increase of straw dry weight had no impact on grain dry weight, while shoot dry weight significantly related to grain dry weight (Fig. 2a and Fig. 2b). Grain dry weight achieved the highest value of 11.8 t/ha when shoot dry weight reached 29.2 t/ha according to the correlation equation. Moreover, leaf area index at silking did not affect the yield levels, while a significant correlation was found between leaf area index at harvest and grain dry weight, suggesting delaying of leaf senescence

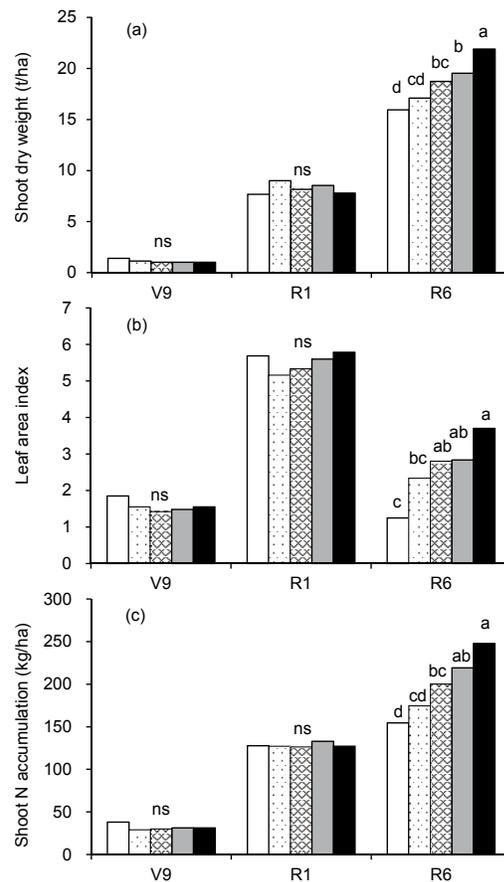


Fig. 1 (a) Shoot dry weight, (b) leaf area index, and (c) shoot nitrogen accumulation at 9 collars stage (V9), silking stage (R1), and physiological maturity (R6) under yield levels of less than 8.25 t/ha (white bars), 8.25–9.75 t/ha (dotted bars), 9.75–11.25 t/ha (net bars), 11.25–12.75 t/ha (grey bars), and greater than 12.75 t/ha (black bars) in Wuqiao experimental station of China Agricultural University from 2006–2011. Bars with the same letters are not significantly different within each developmental stage, $p < 0.05$.

may benefit the increase of grain yield. However, the potential of yield increment through maintaining leaf area was limited (Fig. 2d), i.e., further LAI increment could not improve yield. Nitrogen accumulation in straw and grain were both important for grain dry weight and showed significant correlation with grain dry weight (Fig. 2e and Fig. 2f).

DISCUSSION

Summer maize growing system has a long history in North China Plain, in which sowing date, plant density, and fertilizer input were all under a high level. However, grain yield became static since the

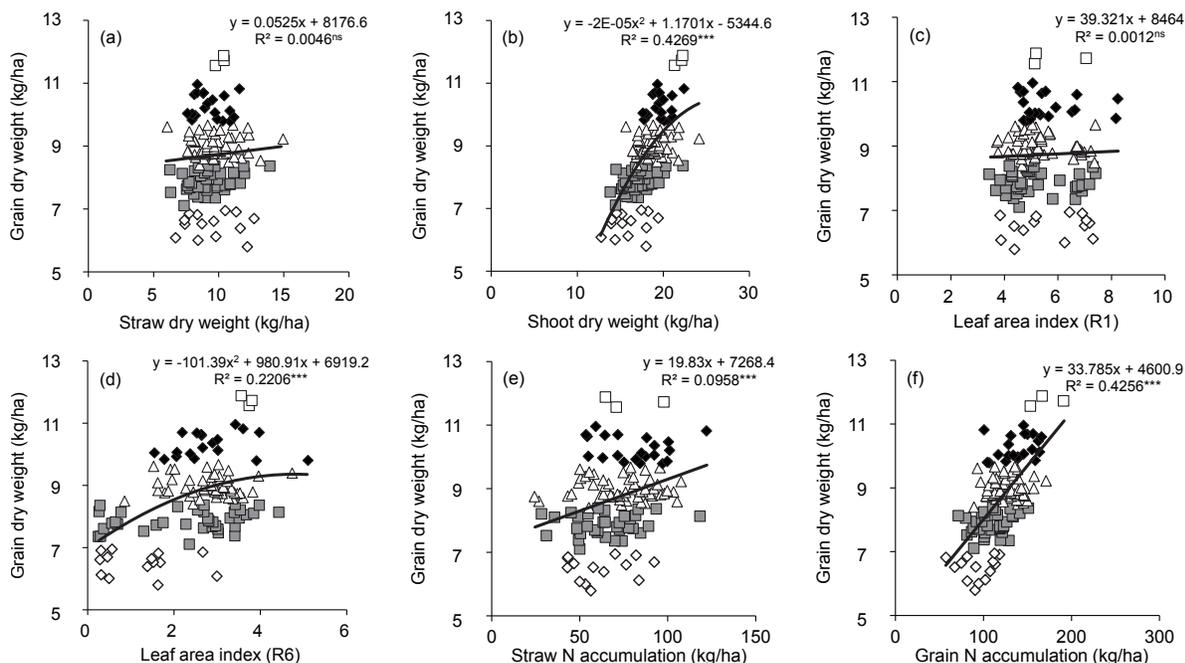


Fig. 2 Correlations between grain dry weight and (a) straw dry weight at physiological maturity, (b) shoot dry weight at physiological maturity, (c) leaf area index at silking stage, (d) leaf area index at physiological maturity, (e) straw N accumulation at physiological maturity, and (f) grain N accumulation at physiological maturity under yield levels of less than 8.25 t/ha (open diamonds), 8.25–9.75 t/ha (grey squares), 9.75–11.25 t/ha (open triangles), 11.25–12.75 t/ha (filled diamonds), and greater than 12.75 t/ha (open squares) in Wujiao experimental station of China Agricultural University from 2006–2011. ^{ns} and ^{***} represent not significant and significant at $p < 0.001$ level, respectively.

2000s. Yield analysis showed that kernel number per ear was the major component positively affected grain yield under plant density of 80 000/ha, while 1000-kernel weight maintained at low values across all yield levels (Table 4). Grain yield in maize is a function of the relationship between assimilates supply to the kernel and inherent potential of the kernel to accommodate assimilates¹⁴. Factors related to kernel number and filling are therefore analysed in the following sections.

Source limitation occurred while hardly to be improved

Dry matter production around silking is important for kernel formation and filling¹⁵, and thus determines the yield level. In our experiment however shoot dry weight and leaf area index at silking at all yield levels were at similar ranges (Fig. 1a). As there were larger kernel numbers for high yield (Table 5), it is obvious that assimilated supply (source) to each kernel was insufficient under high yield. Kernel filling was therefore poor and thus kernel weight was less under high yield (Table 4).

Many field management methods had been ap-

plied to improve source size in order to increase kernel number and weight, such as increasing plant density, nitrogen, and water input^{8,16}. Nevertheless, these measures usually increase lodging risk. We analysed the potential of grain yield increment through increasing total shoot dry weight and leaf area index (Fig. 2). Grain dry weight achieved the highest value of 11.8 t/ha with shoot dry weight of 29.2 t/ha and low harvest index of 0.40 (Fig. 2b). Additionally, the leaf area index and grain dry weight curve show that an increase of leaf area index will not contribute to grain yield increments under the current field management and variety conditions (Fig. 2d). One possibility to improve source strength might be using new varieties with higher lodging resistance and/or leaf photosynthesis capacity, so that the assimilates supply could be enhanced for kernel differentiation and filling afterwards.

Enhancement of sink strength benefit to grain yield increment

It has been reported that the increase of straw production contributed more than the increase of

harvest index to grain production in US Corn Belt¹⁷. While our data demonstrated that further increase of straw dry weight had no effect on grain yield but caused reduction of harvest index (Fig. 2a). Thus improvement of harvest index through enhancing sink strength might be more helpful to increase grain yield with current Chinese variety (Fig. 2b).

Harvest index could be improved by improving the kernel number per unit of land area, i.e., increasing of plant density and/or kernel number per ear. As the relationship between yield level and plant density was weak under the current high density level (Table 4), improving kernel numbers per ear became a more important issue. The processes determining kernel number per ear were highly sensitive to low level of intercepted radiation or N supply¹⁸. In our experiment, straw dry weight, leaf area index and N accumulation at all yield levels were similar before silking, while differences among yield levels occurred after silking (Fig. 1), i.e., high post-silking dry weight and N accumulation as well as greater LAI at high yield level. These data implied stronger photosynthesis and N acquisition capacity of high yield level plants during silking to physiological maturity. When comparing datasets over N application rates and plant densities, it was clear that a yield greater than 11.25 t/ha occurred under optimal N rate (120–180 kg/ha) and optimal plant density (8.25 plants/m²). However, there were more plots who received similar growing condition, while obtained low yield. These suggests that factors other than density and N rate were regulating leaf growth, dry matter accumulation and thus kernel formation after silking.

Moreover, there were still a great potential to improve kernel weight. Thousand-kernel weight of ZD958 was usually around 330 g¹⁹, while it was averagely less than 300 g for all yield level under our experimental conditions (Table 4). The low kernel weight, especially under high yield level, implied problem in kernel filling stage. Kernel weight depends on the potential kernel size established early in kernel filling, and the plant capacity to provide assimilates needed to fulfil this potential during filling²⁰. The early stage of kernel filling was a lag phase, which was a period of rapid water accumulation and endosperm expansion and then sink size was determined²¹. Thus root water acquisition and transpiration of leaves shall contribute substantially to sink size at this stage. However, leaf area at silking showed no difference among yield levels (Fig. 1), suggesting a general poor endosperm expansion of summer maize. After lag phase, dry

matter under high yield accumulated significantly faster than low yield, which was due to slow leaf senescence under high yield (Fig. 1) and finally led to greater grain yield. Nevertheless, kernel weight could be further improved by enhancing leaf function after silking and especially root function needs also be concerned during this period.

Meteorological and soil condition might limit yield potential

Typically, maize variety ZD958 could achieve a kernel number per ear of 500–550¹⁹, while it was insufficient in our experimental area, even under high yield level (Table 4). Our experimental area held a typical semi-humid continental monsoon climate, which received plenty of precipitation but less solar radiation in July and August (Table 1). During this critical period for kernel formation fertilization, lack of sunshine negatively affected the yield formation²². Moreover, temperature before silking was strongly related to maize yield²², thus low temperature at vegetative stage in this area (data not shown) would be another reason of small source size and less kernel differentiation. The low kernel number in high yield limited sink strength and could not drive more assimilates to fill the kernels. Breeding of varieties that matched this climate condition is necessary to further improve the yield.

Moreover, root development might be limited due to poor soil conditions, i.e., high soil bulk density and low nutrient availability (Table 2). Active root N uptake during grain filling increases canopy photosynthesis duration and final grain yield²³. However, leaf senescence occurred in our experiments, which should relate to insufficient nutrient supply from the root. Under this situation, the root could not receive sufficient carbohydrates for structure maintenance within this system, which might lead to root senescence. Methods to enhance leaf and root function during this period should therefore be developed to obtain the target yield (> 12.75 t/ha). Methods such as subsoiling²⁴, N top-dressing after silking, and organic manure application shall be applied in this area to maintain and even improve root function.

Conclusions

Grain yield of summer maize in this area was limited by insufficient kernel number per ear and low kernel weight, which were due to: (1) source limitation before silking, which was hardly ameliorated simply through improving field managements with current variety, (2) leaf and root senescence from

silking to physiological maturity, causing lower sink strength, which limited the assimilate production and translocation to grain and root, additionally, (3) low temperature and low sunshine hours as well as high soil bulk density might be factors limiting kernel development and root expansion, and thus yield formation.

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