Maintenance of Crop Growth through 30 Days after Silking Contributes to Achieving Super-High Yield of Spring Maize

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Abstract: Jilin Province is a major spring maize area of China with the highest regional yield. Nevertheless, a large yield gap existed between actual and potential yield. A super-high yield (> 15 t ha⁻¹) is needed to fulfil the increasing demand. However, yield has been limited due to the lack of knowledge on crop performance in relation to super-high yielding managements. Ten field experiments in Jilin Province from 2008 to 2011 were summarized to understand the growing process of high-yielding spring maize. Plants were categorized into high yield (HY) plants which had a yield > 12 t ha⁻¹, medium yield (MY) plants which had a yield of 9 – 12 t ha⁻¹, and low yield (LY) plants which had a yield < 9 t ha⁻¹. Crop growth during vegetative stages showed no significant differences among yield categories. HY plants grew faster than LY and MY plants after the twelve-collar stage, and the difference became more and more pronounced during silking to 30 days after silking, and even afterwards. Moreover, HY plants had a shorter vegetative period than either LY or MY plants without impacts in vegetative growth, and longer reproductive period, which contributed to better kernel formation and filling. HY plants also had the capacity to maintain a high leaf area index (LAI) at 30 days after silking, which provided for a continuous dry matter accumulation during and after this period and thus resulted in a super-high yield. Hence, special attention should be paid during the 30 days after silking in order to maintain a high photosynthetic capacity and achieve a super-high yield.

Key words: Crop growth rate, Grain yield, LAI, Post-silking dry matter accumulation, Yield category.

Maize (Zea mays L.) is one of the top three food crops in China, providing 33.8% of the food crop in China. Jilin Province located in the North-East of China has a typical continental monsoon climate. Jilin Province is a major spring maize growing zone, contributing 12.1% of maize production and 9.3% of the maize planting area in China (National Bureau of Statistic of China, 2012). The regional average grain yield in Jilin Province has increased in recent years reaching 7.5 t ha⁻¹ in 2011, and this province is the highest maize yield district in China (National Bureau of Statistic of China, 2012). However, a modelled potential yield of 15.4 to 15.9 t ha⁻¹ was reported in North-East China, including Jilin Province, demonstrating a large yield gap between modelled potential yield and actual farm yield (Meng et al., 2013).

Moreover, scientists designed a target grain yield of > 15 t ha⁻¹ (super-high yield) for this area in the 1990s according to the favourable meteorological condition in Jilin Province (Chen et al., 2012). Nevertheless, the average experimental yield in the North-East region of China was 13.6 t ha⁻¹, and farmers’ yield averaged 9.3 t ha⁻¹ ranging from 2.3 to 16.5 t ha⁻¹ in a 2007 – 2008 farmer survey (Meng et al., 2013). Yield differences might be attributed to inefficient crop management (Zhang et al., 2011) or genetic difference of varieties. Although efforts in maize breeding might improve yield in the long term (Tollenaar and Lee, 2002), in the short term it is important to understand crop development to enhance crop growth and improve/stabilize maize yield at a relatively high level in Jilin Province.
Maize yield formation has been thoroughly analyzed in the past decades. Beside the number of ears per area, which is determined by plant density, kernel number per ear contributed to grain yield to a great extent and was very sensitive to the environment around silking (Otegui and Melón, 1997). In addition, kernel weight at physiological maturity depended on the potential kernel size established early in grain filling (Borrás and Westgate, 2006). The formation, abortion and filling of kernels were related to the supply of assimilates, which was determined by photosynthetic capacity of individual plants and population. Hence, grain yield of maize was related to the amount of photosynthate available during the entire growing period, especially near flowering (Tollenaar, 1977). Greater dry matter accumulation was associated with greater green leaf longevity (Rajcan and Tollenaar, 1999), which may contribute to the increase of intercepted solar radiation after silking and thus improve kernel number and kernel weight (Jacobs and Pearson, 1991). It was also demonstrated that most assimilates contributing to grain yield were produced after silking (Simmons and Jones, 1985), thus shoot dry weight at silking had been considered as a predictor of grain yield (Otegui et al., 1995). From these results, it can be illustrated that several days before and after silking were critical for crop development and yield formation of maize. Accordingly, efforts have been made in management practise at the silking stage to achieve a regional high grain yield since 21st century (Chen et al., 2008). However, super-high yield could be achieved only in several small planting areas with intensive inputs regardless of the economic costs and environmental risks (Chen et al., 2012). It is obvious that our knowledge of the super-high yielding spring maize system was insufficient, which hampered further improvements in yield in this area. We need to analyze the stages in addition to silking under high or super-high yielding systems, which may provide solutions and new strategies for achieving yield higher than 15 t ha$^{-1}$ in Jilin Province and North-East China.

We summarized and analyzed datasets of ten field experiments in Jilin Province from 2008 to 2011. The objectives of this study were: (1) to determine the crop growth and dry matter formation in three yield categories; (2) to determine the critical stage for super-high yield formation; and (3) to suggest strategies to further improve grain yield of spring maize system in the Jilin Province.

### Materials and Methods

#### 1. Site description and data sources

Three counties in Jilin Province in the North-East region of China were chosen as target sites according to their differences in geographic and meteorological conditions: (1) Huadian County (42º58’ N, 126º44’ E) is located in the east of Jilin Province; (2) Gongzhuling County (43º30’ N, 124º49’ E) located in the centre of Jilin Province; (3) Qian’an County (44º52’ N, 124º00’ E) located in west Jilin Province. Meteorological data of the three counties were obtained from China Meteorological Data Sharing Service System (www.cdc.cma.gov.cn) and shown in Table 1. Soil properties are also presented in Table 1.

Data used in this paper were based on ten field experiments conducted in the three counties from 2008 to 2011 (Table 2). Three commercial cultivars (JD50, XY335 and ZD958) were planted at different plant densities ranging from 3 to 9 plants per m$^2$. The growing periods (from sowing to physiological maturity) of JD50, XY335 and ZD958 were 149, 146 and 148 d, respectively. In each field experiment, a complete randomized block design was applied with three replicates. We examined the meteorological, cultivar and density differences of the spring maize growing system in Jilin Province, and analyzed the growing characteristics and development of maize in three yield categories, i.e., high yield (HY) with a grain yield (14% water content) greater than 12 t ha$^{-1}$, $n = 45$; medium yield (MY) with a grain yield ranging from 9 to 12 t ha$^{-1}$, $n = 54$; and low yield (LY) with a grain yield less than 9 t ha$^{-1}$, $n = 9$. Only 3 treatments (9 plots in total) achieved yields less than 9 t ha$^{-1}$ during the four experimental years because of the generally high yield levels in Jilin Province. Datasets for MY and HY were equally distributed in all 3 cultivars and all planting densities at the 3 counties. Hence, we analyzed the growing characteristics and development of maize in these 3 yield categories.

### Table 1. Rainfall, > 10ºC effective accumulated temperature (AT), and sunshine hours during maize growing period from May to September from 1992 to 2011, soil type, and soil chemical properties at 0 – 20 cm soil depth of experimental field in Huadian County, Gongzhuling County, and Qian’an county of Jilin Province, China.

| County   | Rainfall (mm) | AT (ºC) | Sunshine hours (hr) | Soil types          | Soil organic matter (g kg$^{-1}$) | Soil total N content | Soil available N content (mg kg$^{-1}$) | Soil available P content (mg kg$^{-1}$) | Soil available K content (mg kg$^{-1}$) |
|----------|---------------|---------|---------------------|---------------------|----------------------------------|----------------------|----------------------------------------|----------------------------------------|----------------------------------------|
| Huadian  | 542           | 2805    | 1003                | Allurial            | 24.3                             | 1.3                   | 129.9                                  | 82.9                                   | 184.4                                  |
| Gongzhuling | 415          | 3022    | 1190                | Haplic phaeozem     | 27.2                             | 1.9                   | 127.9                                  | 80.5                                   | 184.4                                  |
| Qian’an  | 284           | 3078    | 1224                | Light chenozem      | 18.6                             | 1.2                   | 118.5                                  | 29.6                                   | 121.1                                  |

Table 1. Rainfall, > 10ºC effective accumulated temperature (AT), and sunshine hours during maize growing period from May to September from 1992 to 2011, soil type, and soil chemical properties at 0 – 20 cm soil depth of experimental field in Huadian County, Gongzhuling County, and Qian’an county of Jilin Province, China.
2. Field managements

Ridge tillage was applied before sowing each year. The distance between ridges was 60 cm in Gongzhuling and Huadian, while narrow-wide double ridges (90 cm plus 40 cm) were applied in Qian’an. Maize seeds were sown on 22 April to 5 May in Gongzhuling and Huadian, and 9 – 15 May in Qian’an. Crops were harvested by hand in the last week of September at 3 counties according to the maturity and temperature conditions. Fertilization and irrigation were conducted differently according to soil fertility and rainfall of each experimental year and location. Detailed field managements were presented in Table 2. Acetochlor and atlas bacteria were applied directly after sowing to suppress the emergence of weed. Trichogramma and Beauveria bassiana were applied to control corn borer when necessary.

3. Plant sampling and measurements

From 2008 to 2011, growth characteristics and dry matter accumulations were measured at 8 collars (V8), 12 collars (V12), silking (R1), 30 days after silking (end of effective kernel filling period, R130), and physiological maturity stage (R6). A non-disturbed area (final harvest area) was fixed in the center of each plot with an area of 10 m², and this area was used for measuring grain yield and yield components. Three plants were harvested around the final harvest area of each plot. 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 (Dwyer and Stewart, 1986). Leaf, stem and ear dry matters were determined after oven-drying at 80ºC to a constant weight for about 72 hours. At physiological maturity in September, the final harvest area was harvested by hand to determine maize yields. Ten ears were randomly picked within the final harvest area to measure kernel number per ear and 1000-kernel weight (TKW). The grain yield was adjusted to 14% moisture.

4. Data calculation and statistical analysis

The growing days pre- and post-silking stage under three yield categories were recorded and then growing degree days (GDDs) were calculated as growing days of each period multiplied by daily mean temperature minus base temperature, 10ºC (if Tmin < 10ºC then Tmin = 10, if Tmax > 30ºC, then Tmax = 30ºC) (Tollenaar et al., 1979; Kiniry and Keener, 1982). Dry matter translocation (DrMT) was calculated as dry matter differences of stems and leaves between R1 and R6. Then DrMT was divided by dry matter at R1 to represent dry matter translocation efficiency (DrMTE). Contribution of pre-silking dry matter to grain (Cpe, %) was then calculated as a percentage of DrMT occupied in grain weight at R6. Leaf area index (LAI) was calculated as leaf area (LA = length × width × 0.75) per unit of land area. Ratio of kernel and leaves (K/L ratio) was calculated as the number of kernels divided by

| County | Year | Cultivar | Plant density (Plants m⁻²) | Plot size (m²) | Sowing date (mm/dd) | Harvest date (mm/dd) | Irrigation (mm) | N-P₂O₅-K₂O (kg ha⁻¹) | Organic manure (m³ ha⁻¹) |
|--------|------|----------|---------------------------|---------------|---------------------|---------------------|----------------|----------------------|-----------------------------|
| Huadian | 2008 | JD50     | 4, 5, 6, 7, 8             | 48            | 04/22               | 09/29               | 0             | 76-75-75             | 304-75-75                   |
|        |      | XY335    | 8                         |               |                     |                     | 60            |                      |                             |
|        | 2009 | JD50     | 7.5                       | 48            | 05/05               | 09/28               | 0             | 110.7-130-81         | 165.5-0-108                 |
|        |      | XY335, ZD958 | 9                      |               |                     |                     | 15            |                      |                             |
| Gongzhuling | 2008 | JD50     | 4, 5, 6, 7, 8             | 60            | 04/26               | 09/26               | 0             | 110.7-130-81         | 165.5-0-108                 |
|        |      | XY335    | 8                         |               |                     |                     | 180²         | 130-195-247.5        | 270-15-225                  |
|        | 2009 | JD50     | 8.25                      | 60            | 04/29               | 09/19               | 40            | 60-70-80             | 182-30-40                   |
|        |      | XY335    | 6.7, 9                    |               |                     |                     | 40            |                      |                             |
|        |      | ZD958    | 9                         |               |                     |                     | 40            |                      |                             |
|        | 2010 | XY335, ZD958 | 8                      | 60            | 05/03               | 09/25               | 52            | 180²                 | 210²                        |
|        |      | XY335    | 3, 4.5, 6, 7.5, 9         | 52            | 05/04               | 09/28               | 60-70-80      | 182-30-40             |                             |
|        |      | ZD958    | 9                         |               |                     |                     | 40            |                      |                             |
|        | 2011 | XY335    | 8                         | 52            | 05/10               | 09/24               | 52            | 210²                 |                             |
| Qian’an | 2008 | XY335, ZD958 | 9²                   | 65            | 05/09               | 09/27               | 195-255-315   | 270-220-273           |                             |
|        | 2009 | XY335, ZD958 | 9                    | 65            | 05/12               | 09/26               | 195-255-315   | 270-220-273           |                             |
|        | 2010 | XY335, ZD958 | 7.5                   | 65            | 05/15               | 09/26               | 195-255-315   | 270-220-273           |                             |
|        | 2011 | XY335    | 8                         | 52            | 05/20               | 09/24               | 195-255-315   | 270-220-273           |                             |

1) Six replicates for each treatment.
2) 40 mm at three leaf stage, 24 mm at jointing stage, 36 mm at tassel stage, and 80 mm at grain filling stage.
3) 90 mm at sowing, and 30 mm at three leaf, jointing, silking and grain filling stages, respectively.
leaf area at R1. The crop growth rate (CGR) was calculated as daily increase of dry matter weight during the growth periods.

Path coefficient analysis was conducted to determine the contribution of each yield component and growth parameter to grain yield (Li, 1956). Analysis of variance (ANOVA) was performed with general linear model (GLM) procedure of the Statistical Analysis System, version 9.0 (SAS Institute Inc., 2002). The comparisons among different yield categories were based on Duncan’s test at the 0.05 probability level.

Results

1. Roles of yield components on yield formation

Grain yields were classified into three categories, HY with an average yield of 13.2 t ha⁻¹, MY with an average yield of 10.6 t ha⁻¹, and LY with an average yield of 8.3 t ha⁻¹ (Table 3). Ear number ha⁻¹ in HY was similar across the 3 yield categories. Kernel number per ear in HY and MY were similar, and both significantly greater than that of LY. Kernel number per ha was the highest number in HY and the lowest number in LY. Thousand-kernel weight (TKW) tended to decrease with decreasing yield category, but significant differences were not found. Additionally, harvest index significantly increased with the increase in grain yield (Table 3).

The impacts of yield components (X1, ear number ha⁻¹; X2, kernel number per ear; X3, TKW) on grain yield (Y) were checked by multiple regression analysis. Generally, the equation for all yield category was Y = –25613 + 1169.15X1 + 16.12X2 + 16.75X3 (R² = 0.8360, P < 0.05). Under HY, the equation was Y = –20157 + 1491.97X1 + 16.12X2 + 16.75X3 (R² = 0.9162, P < 0.001). Under MY, the equation was Y = –1934.83X1 + 26.74X2 + 30.28X3 (R² = 0.8569, P < 0.001). Under LY, the equation was Y = –11806 + 1169.15X1 + 16.12X2 + 16.75X3 (R² = 0.8360, P < 0.05). Thus, the partial regression coefficients were standardized to compare the importance of three yield components (Table 4). In general, ear number was the most important component, followed by kernel number, and then TKW; however, each component showed different impacts depending on yield category. Ear number played a relatively major role among the yield components for HY. Ear number and kernel number per ear showed similar and strong impact on MY, while kernel number per ear was the most important in LY. TKW had the least impact on grain yield, but still strongly affected grain yield in all categories.

2. Contribution of pre- and post-silking growth to dry matter accumulation

The growing period from sowing to silking (SO – R1) was significantly shorter in HY than in MY and LY, while from silking to physiological maturity (R1 – R6) was significantly longer in HY than in MY and LY. There was no difference in the growing days at these two stages between MY and LY. Moreover, GDDs in HY was the least among yield categories from SO to R1, while the greatest from R1 to R6. Plants in MY obtained the greatest GDD before silking, and the lowest GDD after silking. Generally, there was no significant difference on total growing days and total GDD from SO to R6 among 3 yield categories (Table 5).

Before silking, dry matter accumulation (DrMpe) was similar in all yield categories, while post-silking dry matter accumulation (DrMps) significantly decreased with the decrease in yield (Table 6). In addition, dry matter

### Table 3. Grain yield (14% water content), ear number per ha, kernel number per ear, kernel number per ha, thousand-kernel weight (TKW), and harvest index (HI) in high yield, medium yield and low yield plants in Huadian County, Gongzhuling County, and Qian’an County of Jilin Province, China.

| Yield category | Yield (t ha⁻¹) | Ear number (No. ha⁻¹) | Kernel (No. ear⁻¹) | Kernel (No. × 10⁴ ha⁻¹) | TKW (g) | HI (%) | Number of observations (n) |
|----------------|----------------|----------------------|--------------------|--------------------------|---------|--------|---------------------------|
| High yield     | 13.2 ± 0.8 a¹   | 76352 ± 12092 a      | 507.7 ± 50.3 a     | 3827 ± 391 a             | 340.2 ± 26.7 a | 51.5 ± 5.2 a | 45                      |
| Medium yield   | 10.6 ± 0.9 b    | 64173 ± 10526 b      | 511.5 ± 79.0 b     | 3218 ± 342 b             | 333.1 ± 40.4 a | 48.5 ± 4.5 a | 54                      |
| Low yield      | 8.3 ± 0.1 c     | 68527 ± 21167 b      | 420.1 ± 165.5 b    | 2662 ± 476 c             | 321.0 ± 58.8 a | 42.5 ± 0.8 b | 9                       |

¹ High yield, medium yield, and low yield represented grain yields higher than 12 t ha⁻¹, less than 12 but higher than 9 t ha⁻¹, and less than 9 t ha⁻¹, respectively.

² Figures within each column followed by same letters are not significantly different, p = 0.05; values after mean are standard deviation.

### Table 4. Standard partial regression coefficients between yield and yield components.

| Yield category | Ear number (No. ha⁻¹) | Kernel (No. ear⁻¹) | TKW (g) |
|----------------|----------------------|--------------------|---------|
| High yield     | 1.8571***            | 1.1819***          | 0.9076*** |
| Medium yield   | 1.9266***            | 1.9118***          | 1.2005*** |
| Low yield      | 3.5052***            | 3.9392**           | 1.4534**  |
| All yield      | 1.3423***            | 1.2716***          | 0.5870*** |

¹ High yield, medium yield, and low yield represented grain yields higher than 12 t ha⁻¹, less than 12 but higher than 9 t ha⁻¹, and less than 9 t ha⁻¹, respectively.

² ** and *** represent significant at 0.01 and 0.001 probability.
accumulation from silking to 30 days after silking (DrM 30 ) in high yield, medium yield and low yield plants in Huadian County, Gongzhuling County, and Qian’an County of Jilin Province, China.

### Table 5.
Growing days and growing degree days (GDD) from sowing to silking (SO – R1) and silking to physiological maturity (R1 – R6) in high yield, medium yield and low yield plants in Huadian County, Gongzhuling County, and Qian’an County of Jilin Province, China.

| Yield category | Growing days (d) | Growing degree days (ºC.day) |
|----------------|------------------|-----------------------------|
|                | SO – R1 | R1 – R6 | SO – R6 | SO – R1 | R1 – R6 | SO – R6 |
| High yield     | 88.1 ± 2.2 b ² | 61.3 ± 3.8 a | 149.4 ± 3.7 a | 873.8 ± 92.4 b | 636.3 ± 35.8 a | 1510.1 ± 85.0 a |
| Medium yield   | 96.2 ± 10.2 a   | 55.2 ± 4.3 b | 151.4 ± 7.6 a | 968.6 ± 64.7 a | 572.2 ± 87.3 b | 1540.8 ± 40.9 a |
| Low yield      | 94.0 ± 11.0 a   | 53.7 ± 1.5 b | 147.7 ± 9.7 a | 915.2 ± 84.5 b | 585.9 ± 89.9 b | 1501.1 ± 7.0 a |

1) High yield, medium yield, and low yield represented grain yields higher than 12 t ha⁻¹, less than 12 but higher than 9 t ha⁻¹, and less than 9 t ha⁻¹, respectively.
2) Figures within each column followed by same letters are not significantly different, p = 0.05; values after mean are standard deviation.

### Table 6.
Dry matter accumulation before and after silking (DrMpe, DrMps), dry matter accumulation from silking to 30 days after silking (DrM 30 ), shoot dry matter at maturity (DrM), dry matter translocation (DrMT, t ha⁻¹), dry matter translocation efficiency (DrMTE), and contribution of pre-silking dry matter to grain yield (Cpe), in high, medium and low yield plants in Huadian County, Gongzhuling County, and Qian’an County of Jilin Province, China.

| Yield category | DrMpe (t ha⁻¹) | DrMps (t ha⁻¹) | DrM 30 (t ha⁻¹) | DrM (t ha⁻¹) | DrMT (t ha⁻¹) | DrMTE (%) | Cpe (%) |
|----------------|----------------|----------------|-----------------|--------------|--------------|-----------|--------|
| High yield     | 12.9 ± 1.8 a   | 12.9 ± 1.4 a   | 10.2 ± 1.4 a    | 25.8 ± 3.1 a | 1.7 ± 0.8 a  | 15.8 ± 8.6 a | 15.5 ± 6.7 a |
| Medium yield   | 11.8 ± 2.2 a   | 10.1 ± 2.1 b   | 8.3 ± 1.3 b     | 21.9 ± 2.0 b | 1.2 ± 0.8 a  | 12.0 ± 8.7 a | 12.8 ± 9.4 a |
| Low yield      | 11.5 ± 0.5 a   | 8.2 ± 0.6 c    | 7.2 ± 0.8 b     | 19.7 ± 0.4 b | 1.4 ± 0.9 a  | 15.0 ± 9.0 a | 20.0 ± 12.2 a |

1) High yield, medium yield, and low yield represented grain yields higher than 12 t ha⁻¹, less than 12 but higher than 9 t ha⁻¹, and less than 9 t ha⁻¹, respectively.
2) Figures within each column followed by same letters are not significantly different, p = 0.05; values after mean are standard deviation.
3) Dry matter translocation pre-silking (DrMT) = dry matter difference in leaves + dry matter difference in stems at R1 and R6.
4) Dry matter translocation efficiency (DrMTE) = DrMT / total aboveground dry matter at R1 x 100.
5) Contribution of pre-silking dry matter to grain (Cpe) = DrMT/grain weight at maturity x 100.

3. Crop growth during entire growing period and its contribution to yield

LAI in 3 yield categories showed similar values at V8 stage, but it tended to diverge until R6 (Fig. 1A). At V12 and R1 stages, there were no statistical differences among yield categories, while LAI in HY was significantly higher than that in LY at 30 days after R1 (R1 30). Dry matter accumulation was similar in all three yield categories, at V8, V12 and R1, but significantly higher in HY at R1 30 and R6 (Fig. 1B). DrM in MY was slightly higher than that in LY. The ratio of kernel number and leaf area (K/L ratio) at the R1 stage in LY was less than HY and MY, but statistically no difference due to high variation in HY and MY and low degree of freedom of LY (Fig. 1C). In addition, relationships between yield and LAs at V8, V12, R1, and R1 30 were checked. A significant positive logarithmic correlation between grain yield and LAI at R1 30 was found (Fig. 2), while no clear relationship was found in other stages (data not shown).

Crop growth rate (CGR) in HY at SO – R1 was significantly higher than that in MY and LY although no significant difference was observed in each developmental stage, SO – V8, V8 – V12, and V12 – R1 (Table 7). Moreover, the difference in CGR among yield categories became more pronounced after silking, i.e., CGR decreased with the reduction of yield level, during R1 to R1 30 and R1 30 to R6. Especially, the CGR at R1 30 – R6 was lower in LY than in MY and much lower than that in HY, showing a problem in grain filling in LY (Table 7).

**Discussion**

Kernel number ha⁻¹ (sink size), a combination of kernel number per ear and ear numbers per ha, showed close relationship with yield (Table 3, r = 0.7813***). Additionally, kernel number per ear played major role in grain yield in LY, while ear number per ha, related to plant density, was the most important in MY and HY. The yield
difference between LY and MY was 26.7%, 21% of which was the difference in kernel number. Moreover, yield difference between MY and HY was 24.5%, 19% of which was the difference in ear number. These results show that plant density, plant establishment (determining ear number ha\(^{-1}\) at early stages), and formation of kernels were three important procedures which finally determined the yield under our experimental conditions. Since plant density was usually determined by the variety and seeding rate, kernel onset and pollination are critical for grain yield of spring maize at stages V12 and R1 (Cirilo and Andrade, 1994; Frey, 1981). In addition, kernel weight determined after flowering also contributed strongly to yield increment (Borrás and Gambín, 2010).

The length of the growing period (growing days) had no effect on the separation of yield categories. However, there were significant differences in the lengths of vegetative and reproductive stages among yield categories. Vegetative stage and reproductive stage were separated by the silking stage; and the growth state at the silking stage was commonly used as an indicator of grain yield (Otegui et al., 1995). In LY and MY, plants had a longer vegetative period but shorter reproductive period than in HY, which benefit source (leaf) growth but limited sink (kernel) growth (Allison and Daynard, 1979). This is reflected in the relatively low kernel number to leaf area at the silking stage (Fig. 1C). Different length of vegetative periods had no impact on above-ground dry matter accumulation prior to silking at all three yield categories. However, a longer reproductive period resulted in greater post-silking dry matter (Table 6) and higher yield (Table 3). The high yield category did have a significantly longer reproductive stage although the total growing period of the three yield categories were similar.

Shoot dry weight at silking stage has been reported to be significantly correlated with kernel number and grain yield (Otegui et al., 1995). However, we found that dry matter...
after R1, especially R1 - R1\textsubscript{30} contributed more to the dry matter differences among three yield categories. In addition, crop growth during vegetative stages showed no significant difference among yield categories, while HY plants grew faster than LY and MY plants after V12, and the difference became significant after R1 and even greater after R1\textsubscript{30}. The superiority of CGR in HY plants contributed to high dry matter accumulation after silking, demonstrating that the capacity of continuous growth after silking was essential for achieving a higher yield. Large kernel numbers (large sink size) could be attributed to the faster dry matter accumulation (great source strength) in HY plants. Nevertheless, LY plants lost their growth ability during kernel filling stage due to sink limitation (Table 3), and finally lost yield. These suggested that yield might be further improved through enhancing kernel filling, at around 30 days after silking.

Grain yield of maize is determined by assimilate supply to the grain and inherent potential of the grain to accommodate the assimilate (Jones and Simmons, 1983), which was regulated by leaf photosynthesis and assimilate translocation. As the pre-silking assimilate translocation commonly contributed a small percentage to grain yield (Allison and Daynard, 1979; Table 6), leaf function after silking became very important for both kernel formation and kernel filling. Plants achieving higher yield showed not only greater LAI, but also slower leaf senescence than those in lower yield categories (Fig. 1). HY plants maintained a relatively high LAI during R1 to R1\textsubscript{30}, which was a critical period for determining final kernel number and kernel filling (Borràs et al., 2010; Egharevba et al., 1976; Frey, 1981). Moreover, a logarithmic correlation was observed between grain yield and LAI only at R1\textsubscript{30}, implying the necessity of maintaining leaf function until the end of effective kernel filling. Two strategies might be feasible for maintaining leaf function, i.e., maintaining LAI and/or improving photosynthetic capacity of each leaf at this stage. However, LAIs at R1\textsubscript{30} should be at values higher than 8 in order to achieve a grain yield higher than 15 t ha\textsuperscript{-1} according to the correlation curve (Fig. 2), which was impossible for the varieties used in these studies. Hence, increasing leaf quality (photosynthetic capacity per unit leaf area) through field managements (e.g. nitrogen (N) fertilization) might contribute to the maintenance of leaf photosynthesis at this period. In our experiments, shoot N uptake in MY and LY was significantly less than in HY at R6 and slightly less than in HY at R1 and R1\textsubscript{30} with similar N input and N top-dressing amount (data not shown). These results implied that either soil N supply or root N absorption after R1\textsubscript{30} affected plant N uptake and thus leaf functions. Furthermore, breeding of new varieties tolerant to a high plant density or with superior leaf function could be another solution to further improve the grain yield of spring maize in Jilin Province of China.

**Conclusion**

Kernel number ha\textsuperscript{-1} (sink size) determined the yield of spring maize. Kernel number per ear was most important in LY, while ear numbers per hectare (plant density) in MY and HY. The vegetative period of plants was longer in lower yield categories (LY and MY) than in HY, while the reproductive period was shorter in lower yield categories than in HY. Moreover, pre-silking above-ground dry matter accumulation was not affected by the length of vegetative period in any of the three yield categories, while post-silking dry matter accumulation increased significantly with the increase of reproductive period. Simultaneously, plant growth during vegetative stages showed no significant difference among the three yield categories, while HY plants grew faster than LY and MY plants after V12. HY plants had a capacity to maintain a relatively high LAI at R1\textsubscript{30}, showing the importance of this period for yield improvement. In order to achieve grain yield higher than 15 t ha\textsuperscript{-1}, five strategies might be feasible: (1) increasing the kernel numbers through increasing plant density and/or kernels per ear, (2) maintaining high LAI through 30 days after silking (3) increasing the photosynthetic capacity of single leaf by N top-dressing, (4) enhancing pre-silking assimilates translocation and thus increase harvest index (HI) through N and water managements, and (5) breeding of new varieties with high density tolerance or high photosynthesis capacity of leaf.
Acknowledgements

This work was supported by Key Sci-tech Project of the “12th 5-year-plan” of China (2011BAD16B10-5) and Special Fund for Agro-scientific Research in the Public Interest (201203031). We thank Prof. Xiangzuo Meng, Prof. Ping Zhu, Prof. Huitao Liu, Prof. Wuren Liu, Prof. Shaoqiangian, and Prof. Jun Ren for their cooperation and help in field experiments. We also thank Prof. Dr. Edward Deckard for his contribution on language revision.

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* In Chinese with English abstract.