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Attainable yield achieved for plastic film-mulched maize in response to nitrogen deficit

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ABSTRACT

Nitrogen (N) stress limits the yields of maize (*Zea mays* L.) that have been plastic film-mulched in northwest China. Using the tested Hybrid-Maize simulation model, which was combined with field experiments using four levels of N fertilisers (0, 100, 250 and 400 kg N ha^{-1}), we aimed to understand the variability of the attainable yield in response to N stress under plastic film mulching. We show that the application of N250 or N400 results in 100% simulated potential LAI, which is, thus, close to 100% of the simulated potential of both biomass and grain yield. However, N stress treatments significantly decreased the biomass and grain yields, achieving only 40–50% of the simulated potential (N0 treatment) and 70–80% of the simulated potential (N100 treatment). Growth dynamic measurements showed that N stress significantly decreased the LAI, delaying the source capacity growth (canopies) around the silking stage and resulting in lower final kernel numbers. The lower LAI resulted in decreased dry matter accumulation and allocation during the reproductive stage; this decrease led to a decrease in the kernel growth rate and in the grain filling duration, which resulted in a significantly lower kernel weight. This knowledge could be helpful for the optimisation of N management to close the yield gaps of dryland maize in semi-arid monsoon climate regions.

1. Introduction

Food shortages have seriously restricted the economic and eco-environmental sustainable development of the Loess Plateau in northwest China (Shangguan and Peng, 1999). Spring maize (*Zea mays* L.) is one of the most widely grown grain crops on the Loess Plateau (Xie et al., 2005). Cassman (1999) indicated that the average farm must yield 70–80% of the yield potential to meet the expected increase in food demand; however, the maize yield gap in this region is greater than 50% due to the limited water and N nutrients (Mueller et al., 2012). During the past 30 years, the use of plastic film mulching has effectively solved the water limitation for maize (Xie et al., 2005; Liu et al., 2009); however, the crop growth and yield widely vary in response to changes in the amounts of N fertilisers that are used in this region (Mansouri-Far et al., 2010). Therefore, the effective exploitation of yield gaps of maize crops in response to different N fertilisers to increase crop yields has become an important task to ensure food security and economic development.

N is one of the macronutrients that most limits maize grain yields (Uhart and Andrade, 1995; Varinderpal-Singh et al., 2011). During the past 30 years, the maize yield has markedly increased due to the increased use of N fertilisers by farmers (Cassman, 1999). The largest effects of N were evident in the crop growth, which is measured by the leaf area index (LAI), by biomass production (Lawlor, 1995), and by the grain yield component. Furthermore, the N effects on kernel number strongly correlated with the crop growth rate during the critical period for kernel set, which is around the silking stage (Andrade et al., 2002). The use of N fertiliser under the given climatic conditions to increase the crop yield and to decrease the yield gaps must be further investigated. However, there is little information available regarding how the attainable yields are affected by N fertilisers in semi-arid areas.

The yield potential is the yield that can be achieved when an adapted cultivar is grown with minimal environmental stress under best management practices (Cassman, 1999). Although the crop yield potential is difficult to measure under actual field conditions, crop simulation models can provide reasonable estimates of the functional yield potential in a given environment. To understand how the yield gap responds to variations in the N fertilisers, we used a modified version of the Hybrid-Maize model (Yang et al., 2004, 2006) to estimate the growth and yield potential of maize under plastic film mulching. In addition to the crop simulation model, maize plots in a typical arid region on the Loess Plateau were treated with different N fertiliser levels under plastic film mulching conditions. The objectives of this study were (1) to determine the

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maize growth response to various N fertiliser application rates, (2) to assess the yield gaps of rain-fed maize in N deficient conditions, and (3) to better understand the key factors that drive the yield gaps. The results from this study will be used to guide N management strategies to increase maize production in local and in other related regions.

2. Materials and methods

2.1. Crop model evaluation

The Hybrid-Maize model is a process-oriented model (Yang et al., 2004, 2006) that simulates maize development and growth on a daily time-step under growth conditions without limitations from nutrient deficiencies, toxicities, insect pests, diseases, or weeds. This model has been developed by the University of Nebraska-Lincoln, USA, widely tested under rain-fed and irrigated conditions and applied to the US corn-belt (Grassini et al., 2009, 2011a, 2011b), South Asia (Timsina et al., 2010), and China (Chen et al., 2011).

The original version of the Hybrid-Maize model uses air temperature to simulate all crop biological processes. The new plastic film mulching module, which is based on the Hybrid-Maize model, was developed to simultaneously consider topsoil temperature and evaporation. Therefore, the new plastic film mulching module was modified to use measured temperatures underneath the plastic film (5 cm depth) to simulate crop development and growth, whereas air temperature remains used for physiological processes, which include photosynthesis and respiration. In this modified version, soil evaporation is assumed to reduce to 20% of that without plastic film before sheet break. However, this assumption does not significantly affect actual evapotranspiration (ET) because soil evaporation is much lower than crop transpiration.

In this study, the new module is first applied to estimate the yield potential under plastic film mulching (FM) conditions on the Loess Plateau in China. Nevertheless, the application of the modified Hybrid-Maize model with the new FM module should be tested.

2.2. Site description

The field study was conducted at the *Changwu* experimental station (35.28° N, 107.88° E, approximately 1200 m above sea level), which is in a typical dryland farming area on the Loess Plateau. Between 1960 and 2009, the average annual precipitation in the area was 578 mm, and the average annual temperature was 9.7 °C. According to the international soil classification (Soil Survey Staff, 2003), the soil has been mapped as Cumuli-Ustic Isohumosols (Gong et al., 2007), with 4% sand, 59% silt, and 37% clay; the bulk density of the topsoil was 1.3 g cm^{-3}, with a pH of 8.4.

The field experiments were conducted in 2007 and 2009 for Experiment 1 and from 2010 to 2011 for Experiment 2. The organic matter content, as determined by the Schollenberger method, was 11.8 g kg^{-1}. The total N content, as determined by the Kjeldah method, was 0.87 g kg^{-1}. The phosphorus content, as determined by the Olsen-P test, was 14.4 mg kg^{-1}. The NH_4OAc-extractable K content was 144.6 mg kg^{-1}. At the beginning of each experiment, the mineralised N content at planting in the upper 100 cm soil, as determined by the continuous-flow analytical system, was 115.9 kg N ha^{-1} (2007) and 74.9 kg N ha^{-1} (2010).

2.3. Experimental design and field management

In this study, all plots were laid out with a pattern of two ridges and a furrow, which were mulched by one plastic film along the longitudinal axis. The ridges were created in an alternating pattern that consisted of large and small ridges 60 cm and 40 cm wide and 10 cm and 15 cm high, respectively; both ridges were mulched with one piece of white plastic film that was 120–130 cm wide, and soil was placed on top of the pieces to hold the pieces down at the points where the sheets met. Adjacent ridges were separated by furrows, in which the maize was planted using a hole-sowing machine; therefore, the rainwater could be harvested and could reach the soil along the planting hole.

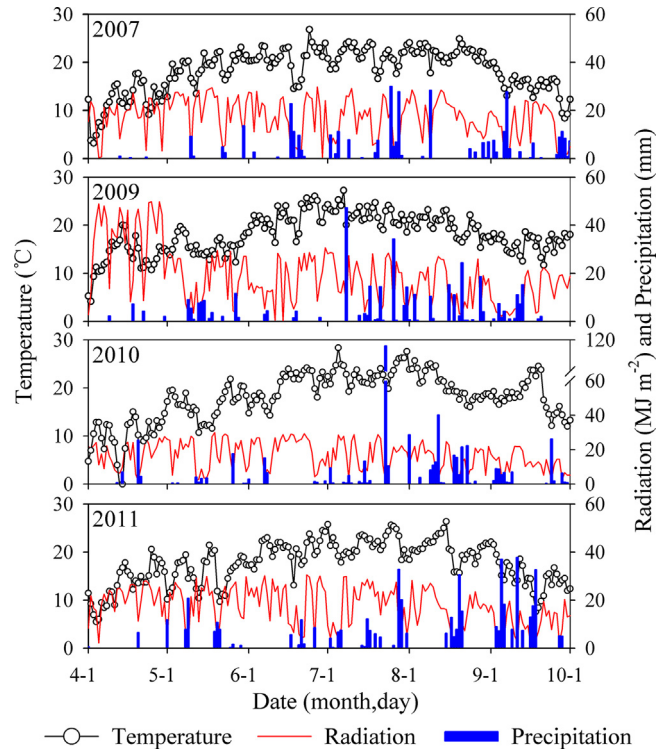

Fig. 1. Daily meteorological data during the four monitored spring maize growing seasons in 2007, 2009, 2010, and 2011 at the *Changwu* experimental station.

The daily weather data at the site during the experiment periods were measured at the Changwu meteorological monitoring station, which is a standard weather station that is situated at the *Changwu* experimental station. Daily meteorological information during each of the maize growing seasons is presented in Fig. 1. Precipitation during the period from May to September amounted to 446 mm in 2007, 374 mm in 2009, 496 mm in 2010 and 487 mm in 2011. Compared with the average precipitation over the last 50 years (422 mm, 1957–2006), except in 2009, the other three years were wet years. The mean air temperature from May to September was 19.1 °C in 2007, 18.7 °C in 2009, 19.6 °C in 2010, and 18.6 °C in 2011.

2.3.1. Experiment 1

The model validation experiments were conducted between 2007 and 2009 (Table 1). The plastic film mulching practices were arranged in a completely randomised block design. The size of each experimental plot was 50.7 m^2 (7.8 m × 6.5 m), with four replicates for each treatment that was performed in 2007, and 56 m^2 (8 m × 7 m), with three replicates for each treatment that was performed in 2009. Spring maize (*Zea mays* L.) pioneer 335 and Shendan 10 varieties were sown 5 cm deep, with 85,000 and 68,000 plants ha^{-1}, respectively, on April 20, 2007. Additionally, the pioneer 335 variety was sown at densities of 85,000 and 65,000 plants ha^{-1} on April 21, 2009. The water supply for each experimental plot was solely dependent on the natural rainfall.

In 2007, 110 kg N ha^{-1} in the form of urea (N 46%), 50 kg P ha^{-1} in the form of calcium superphosphate (P_2O_5 12%), and 100 kg K ha^{-1}

Table 1
Experiment to test the applicability of the new plastic film mulching module based on the Hybrid-Maize model for a 2-year (2007 and 2009) data set collected in *Changwu* experimental station.

Years	Varieties	Plant density	Total biomass (t ha^{-1})		Grain yields (t ha^{-1})	
		Plants ha^{-1}	Observed	Simulated	Observed	Simulated
2007	Pioneer 335	85,000	24.9 ± 1.6	22.2	14.9 ± 1.3	13.0
	Shendan 10	68,000	24.3 ± 2.2	21.0	13.3 ± 1.2	11.5
2009	Pioneer 335	85,000	20.3 ± 0.7	17.9	12.5 ± 0.6	13.8
	Pioneer 335	65,000	17.9 ± 0.5	16.7	11.8 ± 0.6	12.8

Values of both the observed total biomass and grain yields are given as the mean ± the standard error of the mean (n = 4 in 2007, n = 3 in 2009).

in the form of potassium sulphate (K_2O 45%) were spread over the soil surface as a base fertiliser. Additional N, which was in the form of urea, was applied at the jointing stage at a rate of 80 kg N ha^{-1} and at the tasselling stages at a rate of 90 kg N ha^{-1}. In 2009, 90 g N ha^{-1} in the form of urea (N 46%), 40 kg P ha^{-1} in the form of calcium superphosphate (P_2O_5 12%), and 80 kg K ha^{-1} in the form of potassium sulphate (K_2O 45%) was spread as a base fertiliser. Additional N, which was in the form of urea (N 46%), was applied at a rate of 67.5 kg N ha^{-1} at the jointing and tasselling stages in the plots with a density of 65,000 plants ha^{-1}. In the plots with a density of 85,000 plants ha^{-1}, 112 kg N ha^{-1} in the form of urea (N 46%) was spread as a base fertiliser. Additional N, which was in the form of urea, was applied at the jointing and tasselling stages at a rate of 84 kg N ha^{-1}. The nutrient management plan for both years aimed to eliminate the nutrient limitations for maize growth.

We used the Hybrid-Maize model in combination with the daily weather data and the daily actual topsoil (0–5 cm) temperature to simulate the total biomass and grain yield under FM treatment for both years. The daily topsoil (0–5 cm) temperature was recorded manually (using a Geothermometer) between 7:00 h–7:30 h and 14:30 h–15:00 h, and the temperature was averaged to obtain the mean daytime soil temperature. For this simulation, the actual dates of sowing, silking and maturity, as well as the plant population, were required. In particular, based on the results of Wang et al. (2011), the soil evaporation was reduced by 80% under the plastic film mulch during the entire growing season.

2.3.2. Experiment 2

The N level experiments were conducted during 2010 and 2011. Spring maize (*Zea mays* L.) pioneer 335 was sown at a final density of 85,000 plants ha^{-1} under FM in each plot. Four fertilisers that contained different levels of N were applied to the established maize plots; these fertilisers contained 0 (serious N stress; N0), 100 (low N stress; N100), 250 (optimised N application, control; N250) or 400 (excessive N application; N400) kg N ha^{-1} in the form of urea (N 46%). In each treatment (except N0), 40% of the total N fertiliser, which was composed of 40 kg P_2O_5 ha^{-1} in the form of calcium superphosphate (P_2O_5 12%) and 80 kg K_2O ha^{-1} in the form of potassium sulphate (K_2O 45%), was used as a base fertiliser. Additional N (30% of the total N fertiliser) was applied in the furrows in the form of urea (N 46%) using a hole-sowing machine at the jointing and tasselling stages. The treatments were applied to 56 m^2 (8 m × 7 m) plots that were arranged in a completely randomised block design, with four replicates per treatment. The water supply for each treatment was solely dependent on the natural rainfall. In addition, the daily topsoil (0–5 cm) temperature was manually recorded in each plot.

2.4. Plant sampling

The standard maize developmental stage system was used to identify the growth stages of the planted crop (Ritchie et al., 1992). For each plot, the dates at which >50% of the plants first reached the vegetative stage (VS, from seedling emergence to silking) and the reproductive stage (RS, from silking to physiological maturity) were recorded. Aboveground plant samples were harvested, and the maize dry matter was determined at the sixth leaf stage (V6), the tenth leaf stage (V10, only in 2011) or the twelfth leaf stage (V12), the silking stage (R1), the milk stage (R3), the dent stage (R5, except in 2009) and at physiological maturity (R6). Three adjacent plants in a row were sampled randomly from each plot; the samples were taken at least 1 m from the plot edges and 0.5 m from previous sample sites. At each sampled stage, samples were harvested by cutting off the shoot at the first nodule on the stem. The harvested shoots were heated at 105 °C for 30 min and were then dried at 75 °C to a constant weight before calculating the biomass. The total above ground biomass in each plot was expressed as kg dry matter ha^{-1}.

2.5. Leaf area index (LAI) measurement

The area of each fresh leaf from the sampled plants was determined immediately after each sampling (McKee, 1964). The leaf area index (LAI) was calculated as the leaf area × plant density (stated in number of plants per square metres).

2.6. Grain development sampling

The silking dates (R1, 50% plants in a plot with silks emerged) were recorded for 50 tagged plants in each plot; these plants were then used for subsequent sampling in 2010 and 2011. In all treatments, the entire ears of three randomly selected plants were harvested at 5 days intervals, which began 10 days after silking and continued until physiological maturity (Sala et al., 2007). After sampling, the entire ear and the surrounding husk were immediately enclosed in an airtight plastic bag and transported to the laboratory in an insulated container.

Superior kernels were defined as the kernels that were in the basal part of the ear; the conversion of these kernels to dry matter and the examination of translocation material were the priority (Setter and Parra, 2010). Conversely, inferior kernels were defined as the kernels that were in the apical part of the ear. The sampled ears were placed in a humidified box, and the husks were removed. The kernels were then extracted, and the kernels from the apical, middle, and basal thirds of each ear were separated. The fresh weight of each part of the ear was measured immediately after sampling, and the number of kernels in each third of the ear was recorded. The sampled kernels were then dried to a constant weight at 75 °C, and their dry weight was determined. The average weight of an individual kernel was then calculated as the total mass (mg) of the kernels in each section of the ear divided by the number of kernels within that section.

2.7. Crop harvest

Maize cobs were harvested gradually when ripe, on 27–28 August 2007, 17 September 2009, 12 September 2010, and 23 September 2011. The crop biomass and grain yield were measured

for all of the plants in a 10-m^2 area in each plot. The biomass and grain yield were determined based on the average of four plot replicates, and all of the samples were dried to a constant weight in a fan oven at 75 °C. The total above ground biomass (dry matter) in each plot was expressed in terms of t ha^{-1}. The grain yield at 15.5% moisture content was expressed in terms of t ha^{-1}.

2.8. Data calculation and statistical analyses

The normalised root mean square error (NRMSE) was calculated as described by Sepaskhah et al. (2011):

$$NRMSE = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{nO_{avg}^2}} \quad (1)$$

where S_i is the simulated data, O_i is the observed data, O_{avg} is the mean of the measurement values and n is the number of pairs of simulated and observed data. $NRMSE$ ($NRMSE_{\text{Total}}$ and $NRMSE_{\text{Grain}}$) was calculated as the dry matter of both the total biomass and the grain.

The kernel growth rate and the duration of the linear grain filling phase were determined by fitting a two-line model to the kernel dry weight data, which were plotted against the growing degree days (GDD > 0 °C) after silking (Maddonni et al., 1998):

$$\text{KW} = a + bGDD, \quad \text{for} \quad \text{GDD} \le c, \quad (2)$$

$$\text{KW} = \text{maximum kernel weight}, \quad \text{for} \quad \text{GDD} > c, \quad (3)$$

where KW is the kernel weight, a is the Y-intercept (mg), b is the rate of grain filling (mg °C day^{-1}) and c is the total duration of the grain filling (°C days). This two-line model was fitted to the kernel dry weight data using the SAS 8.1 system.

The growing degree days (GDD, >0 °C) within the reproductive stages (RS, from silking to physiological maturity) were calculated based on the daily meteorological data from the *Changwu* meteorological monitoring station. The GDD (°C d) during the reproductive stages was calculated using the following equation (McMaster and Wilhelm, 1997):

$$GDD = \sum_{Silking}^{Maturity} (T_{mean} - T_{base}) \quad (4)$$

where T_{mean} is the daily mean air temperature, and T_{base} is the base temperature of 0 °C (Muchow, 1990). The mean daily air temperature was calculated as the average of the hourly air temperatures that were registered at a weather station, which was located approximately 50 m from the experimental plots. All of the T_{mean} values <0 were considered effectively equal to 0 °C (Arnold, 1974).

The effects of the treatments on the measured parameters were evaluated using a one-way ANOVA. When the F-values were significant, the least significant difference (LSD) test was used to compare the differences in the means between treatments according to Duncan's new multiple range tests. In all cases, the differences were deemed to be significant when $p < 0.05$.

3. Results

3.1. Model validation and yield potential estimation

The new plastic film mulching (FM) module of the Hybrid-Maize model was tested in 2007 and 2009 (Table 1). The results indicated that the values that were estimated for the two maize varieties were close to the measured values of the final biomass. The grain yields were also estimated with a high degree of accuracy for both years.

The simulation results for both the shoot biomass and the grain dry matter agreed with the observed data (Fig. 2). The correlation analysis showed that the estimated values predicted both the shoot biomass (Fig. 3a, $NRMSE_{\text{Total}} = 0.168$) and the grain dry matter dynamics (Fig. 3b, $NRMSE_{\text{Grain}} = 0.147$) extremely accurately. These results indicated that the new FM module of the Hybrid-Maize model could accurately estimate the growth dynamics of

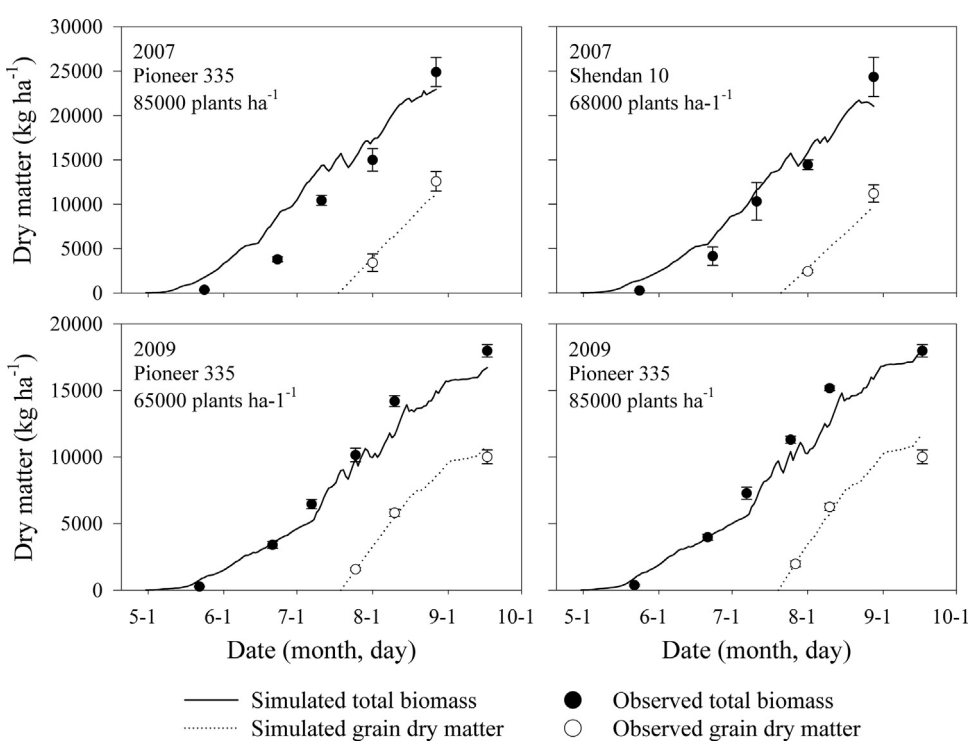

Fig. 2. Hybrid-Maize-simulated and observed growth dynamics from emergence to maturity under plastic film mulching conditions in 2007 and 2009 at *Changwu* experimental station.

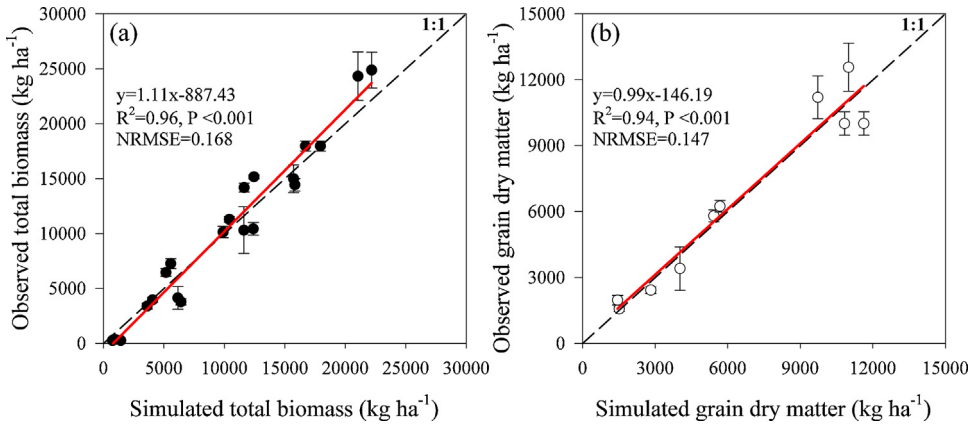

Fig. 3. Correlation analysis between simulated and observed values of total biomass (a) and grain dry matter (b).

biomass and grain in this region. Therefore, it was concluded that the new module could be used for the accurate estimation of the total maize biomass and grain yield under plastic film mulching conditions during the entire growing season in the study region.

Based on the new FM module, which predicts the effects of plastic film mulching, we estimated the potential growth dynamics of the LAI, shoot biomass and grain dry matter during the entire growing season for both years. The values of the maximum LAI, final biomass and grain yield were also estimated. The simulated LAI potential was 5.9 in 2010 and 5.7 in 2011. The simulated biomass and grain yield potential were 21.4 t ha^{-1} and 13.5 t ha^{-1}, respectively, in 2010, and the simulated biomass and grain yield potential were 21.9 t ha^{-1} and 13.9 t ha^{-1}, respectively, in 2011.

3.2. LAI dynamics in plots subjected to different N fertilisers

The LAI increased dramatically during the VS, peaked at the R1 stage, and then declined after the silking stage in all treatments (Fig. 4). The LAI values for the entire growth season significantly increased with the addition of N fertilisers in a dose-dependent manner from the 0 to 250 kg ha^{-1} treatments; there was no difference between the N250 (CK)- and N400 (excessive N)-treated plots. The N0 treatment had the lowest LAI value and the largest difference from the observed to the simulated potential LAI during each development stage due to N stress. Compared with the N0 treatment, the application of N100 (low N stress) fertiliser clearly accelerated LAI beginning at 40 days after sowing and, therefore, resulted in a relatively small difference between the observed and the simulated potential LAI. Both the N250 and the N400 treatments achieved 100% of the simulated potential LAI through the RS stage (from R1 to R6), during which the LAI maintained a high level.

3.3. Shoot biomass and grain dry matter accumulation in plots that were subjected to different N fertilisers

The observed shoot biomass increased dramatically during the entire growth season (Fig. 5a and b) and was consistently and significantly higher when the plots were treated with increasing rates of N fertilisers from N0 to N250. The N0 treatment resulted in serious N stress, thereby producing the least shoot biomass, which resulted in the largest yield gaps of simulated potential shoot biomass. Compared with the N0 treatment, the application of N100 resulted in an increase in the accumulated biomass beginning at 40 days after sowing and significantly induced smaller yield gaps of simulated potential ($p < 0.05$). The application of the N250 and N400 treatments also led to a greater accumulation of biomass and smaller yield gaps; however, there was no significant difference ($p < 0.05$) between these treatments during the entire growth period in both study years.

Similar results were found in the grain growth dynamics for both years (Fig. 5c and d). Both the N250 and N400 treatments closed the yield gaps and reached 100% of simulated grain yields. Both N stress treatments (N0 and N100) resulted in lower amounts of grain dry matter, particularly during the R5–R6 period; therefore, these treatments resulted in a yield gap.

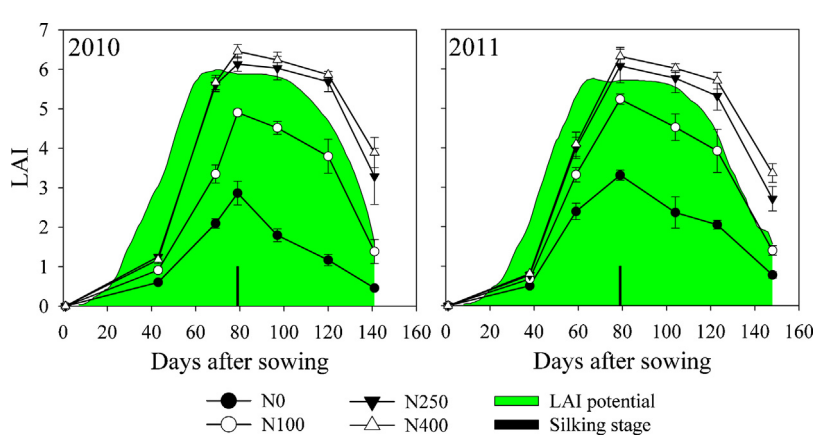

Fig. 4. Changes in leaf area index (LAI) over the growing season under different N fertilizers in 2010 and 2011.

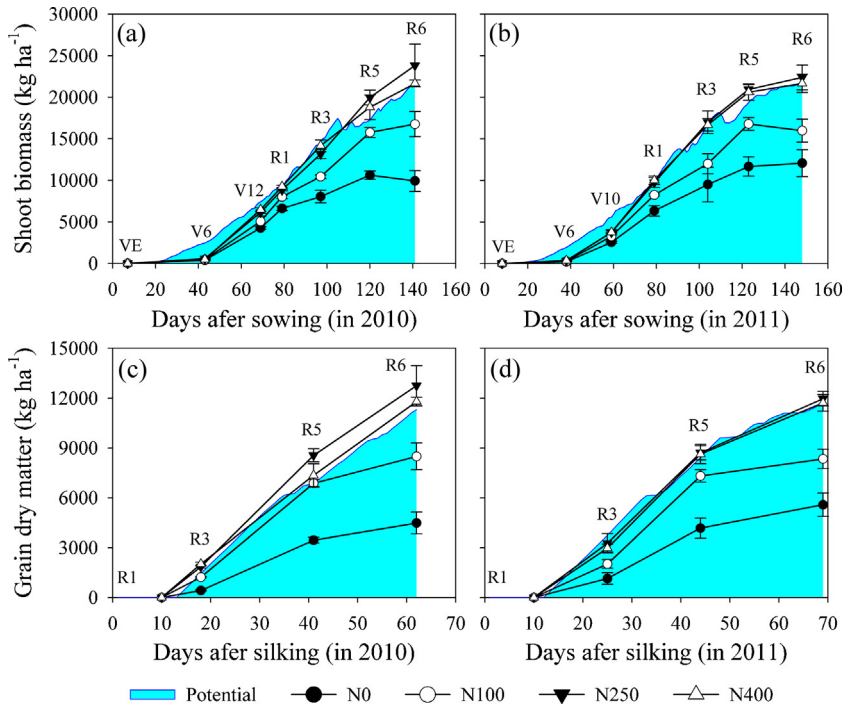

Fig. 5. Development of shoot biomass (a, b) and grain dry matter (c, d) under different N fertilizers rates in 2010 and 2011.

3.4. Dry matter allocation during the VS and RS in plots that were subjected to different N fertilisers

The total dry matter that accumulated during both the VS and RS significantly increased with the addition of N fertilisers from N0 to N250. The increase in the total dry matter during the RS was clearly higher than the increase during the VS period in the N fertiliser-treated plots for both years. Compared with the N250 treatment, the N400 treatment did not result in an increase in dry matter during both the VS and RS periods (Table 2).

The biomass allocation during the VS decreased as the rate of N fertiliser application increased from 0 to 250 kg ha^{-1}; however, the biomass allocation did not decrease with the highest N level (400 kg ha^{-1}) (Table 2). During the RS, the biomass allocation increased as the application rate of N fertilisers increased from 0 to 250 kg ha^{-1} but did not further increase with the 400 kg ha^{-1} N fertiliser rate.

The amounts of biomass that were achieved from simulating the potential biomass significantly increased with the addition of 0 to 250 kg ha^{-1} N fertilisers during the VS, and this increase was greater during the RS (Table 2). Compared with the N250 treatment, the N400 treatment only slightly increased the amount of biomass that was achieved from the potential biomass during the VS; however, the opposite effects occurred during the RS period in both years.

3.5. Kernel growth patterns

The kernel growing progress showed variations between the treatments with different application rates of N fertilisers during the effective grain filling period for both years (Fig. 6). The N0 treatment (serious N stress) significantly decreased the growth rates of the effective grain filling period. Relative to the N0 treatment, the other three treatments had higher kernel growth rates; however, there was no significant difference between the three treatments. The N stress treatment also decreased the duration of the effective grain filling period in both years (Fig. 6). Compared with the N0 treatment, the grain filling duration was 75–116 °C d longer in the N100 treatment, 198–203 °C d longer in the N250 treatment, and 161–203 °C d longer in the N400 treatment (Table 3).

The N0 treatment resulted in the lowest kernel growth rate and in the shortest grain filling period, which, therefore, resulted in the lowest final kernel weight. Because of the higher growth rates and the longer grain filling period, the final kernel

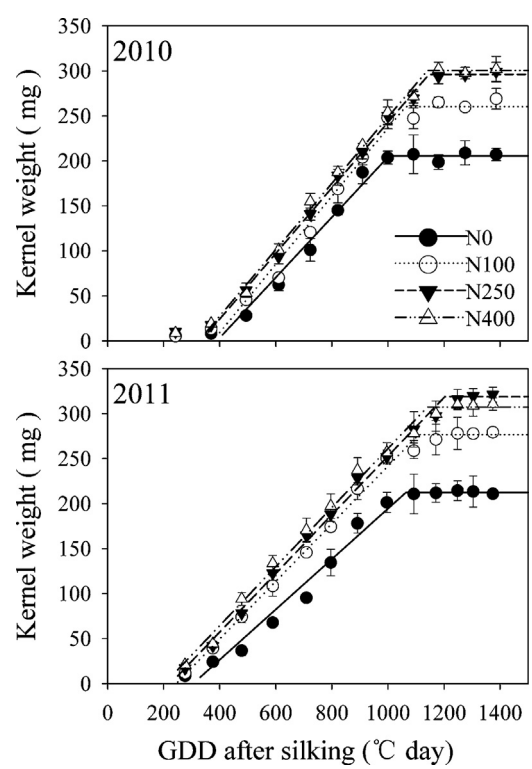

Fig. 6. Mean kernel weight versus growing degree days (GDD > 0 °C) after silking under different N fertilizers rates in 2010 and 2011.

Table 2
The dry matter accumulated, the allocation, and the potential achieved of the total biomass during the vegetative (VS) and reproductive (RS) stages subject to different N fertiliser rates in 2010 and 2011.

Years	N level	Vegetative stage			Reproductive stage		
		Dry matter (t ha^{-1})	Allocation (%)	Achieved of simulated potential (%)	Dry matter (t ha^{-1})	Allocation (%)	Achieved of simulated potential (%)
2010	N0	6.6 d	66.8 a	70.5 d	3.3 d	33.2 c	27.5 d
	N100	8.0 c	47.9 b	85.4 c	8.7 c	52.1 b	72.8 c
	N250	8.8 b	37.1 c	94.0 b	15.0 a	62.9 a	125.0 a
	N400	9.3 a	42.7 bc	98.5 a	12.4 b	57.3 ab	103.4 b
2011	N0	6.3 c	52.5 a	65.7 c	5.7 c	47.5 b	47.0 c
	N100	8.3 b	51.6 a	85.5 b	7.7 b	48.4 b	63.4 b
	N250	9.7 a	43.4 b	100.8 a	12.7 a	56.6 a	103.8 a
	N400	10.0 a	46.2 b	103.7 a	11.7 a	53.8 a	95.6 a

The values given represent the mean ($n = 4$). The values followed by different letters within a column in each year are significantly different ($p < 0.05$) by the least significant differences of Duncan's new multiple range test.

Table 3
Kernel number per plant, kernel weight, kernel growth rate and the duration of the effective grain filling period under different N fertiliser rates in 2010 and 2011.

Years	N level	Kernel growth rate (mg °C day^{-1})	Effective grain filling duration (°C day)	Kernel weight (mg kernel^{-1})	Kernel number (plant^{-1})
2010	N0	0.339 b	588 c	205 c	281 c
	N100	0.378 a	663 b	260 b	570 b
	N250	0.364 a	786 a	296 a	696 a
	N400	0.368 a	791 a	301 a	706 a
2011	N0	0.280 b	731 c	212 c	268 c
	N100	0.328 a	847 b	276 b	553 b
	N250	0.331 a	934 a	319 a	690 a
	N400	0.327 a	892 a	307 a	717 a

The values given represent the mean ($n = 4$). The values followed by different letters within a column in each year are significantly different ($p < 0.05$) by the least significant differences of Duncan's new multiple range test.

weights were 55–64 mg kernel^{-1} greater for the N100 treatment, 91–107 mg kernel^{-1} greater for the N250 treatment, and 95–96 mg kernel^{-1} greater for the N400 treatment (Table 3). In addition, the N stress significantly decreased the total grain numbers and resulted in the lowest final kernel numbers in both years (Table 3). Compared with the N0 treatment, the kernel number was 285–289 kernels greater for the N100 treatment, 415–422 kernels greater for the N250 treatment, and 425–449 kernels greater for the N400 treatment.

The kernel growth patterns in each ear position varied with the different N fertiliser rates (Fig. 7). The superior kernel had higher growth rates and a longer grain filling period than the middle and inferior kernel weights. The N0 treatment resulted in the lowest growth rates and in the shortest grain filling period in each ear

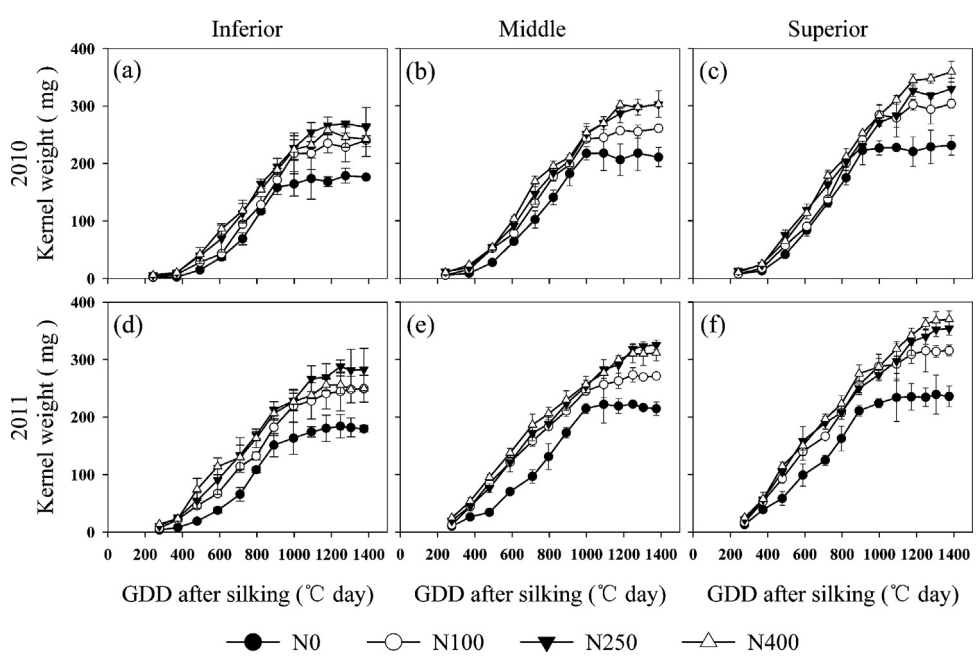

Fig. 7. The development of kernel weights in the inferior, middle, and superior of the maize ear versus growing degree days (GDD) after silking under different N fertilizers rates in 2010 (a, b, c) and 2011 (d, e, f).

Table 4
The productivity and the potential achieved of both the total biomass and grain yields (at 15.5% moisture content) subject to different N fertiliser rates in 2010 and 2011.

Years	N level	Biomass		Grain yields	
		Observed (t ha^{-1})	Achieved of simulated potential (%)	Observed (t ha^{-1})	Achieved of simulated potential (%)
2010	N0	9.9 c	46.4 c	5.3 c	39.2 c
	N100	16.8 b	78.3 b	10.0 b	74.2 b
	N250	23.8 a	111.4 a	15.1 a	111.4 a
	N400	21.7 a	101.3 a	14.0 a	103.0 a
2011	N0	12.1 c	55.2 c	6.6 c	47.6 c
	N100	16.0 b	73.1 b	9.9 b	71.2 b
	N250	22.4 a	102.5 a	14.2 a	102.2 a
	N400	21.7 a	99.1 a	13.9 a	100.1 a

The values given represent the mean ($n = 4$). The values followed by different letters within a column in each year are significantly different ($p < 0.05$) by the least significant differences of Duncan's new multiple range test.

position. Compared with the N0 treatment, the other N fertiliser treatments significantly increased the kernel growth rate at each position; however, there was no significant difference between the three treatments. The duration of the grain filling period in each ear position increased with the increasing N fertiliser application rates, particularly in the superior kernel. The N250 and N400 treatments resulted in the largest kernel weight in the middle and superior positions of the ear.

3.6. *Biomass and grain yields in plots that were subjected to different N fertiliser rates*

Both the biomass and grain yields increased ($p < 0.001$) linearly with the increase in the application of N fertiliser from N0 to N250; however, there was no difference between the N250 and N400 treatments. The comparative analysis shows the differences in the attainable biomass and in the achieved yield in response to the different N fertiliser rates in both years (Table 4). The N stress treatments significantly decreased the biomass and the grain yields, achieving only 40–50% of the simulated potential in the N0 treatment; this yield gap was closed in the N100 treatment, where 70–80% of the simulated potential was achieved. The application of 250 kg ha^{-1} N fertiliser completely closed the yield gaps and resulted in 100% of the simulated yield potential.

3.7. *Biomass, grain yield, kernel number and kernel weight in response to LAI*

A higher maximum LAI value should theoretically benefit plant growth and kernel development. When all of the treatments in both years were considered, the biomass ($R^2 = 0.93$, $p < 0.001$; Fig. 8a) and the grain yield ($R^2 = 0.95$, $p < 0.001$; Fig. 8b) were positively correlated with the measured maximum LAI. Similar results were found for both yield components (kernel number and weight). The final kernel number ($R^2 = 0.98$, $p < 0.001$; Fig. 8c) and weight ($R^2 = 0.97$, $p < 0.001$; Fig. 8d) were closely correlated with the measured maximum LAI.

4. Discussion

The Hybrid-Maize model has been widely tested without limitations from nutrients under rain-fed and irrigated conditions (Yang et al., 2006; Liu et al., 2008). In this study, we first introduced the new FM module of the Hybrid-Maize model and tested the applicability of this module for rain-fed maize that is subject to plastic film mulching on the Loess Plateau. The test results revealed that the FM module could accurately estimate the growth dynamics of both biomass and grain without N limitations under plastic film mulching conditions. Grassini et al. (2011a) documented that, in irrigated maize systems in the western U.S. Corn Belt, the average actual yield ranged from 12.5 to 13.6 t ha^{-1}. The results

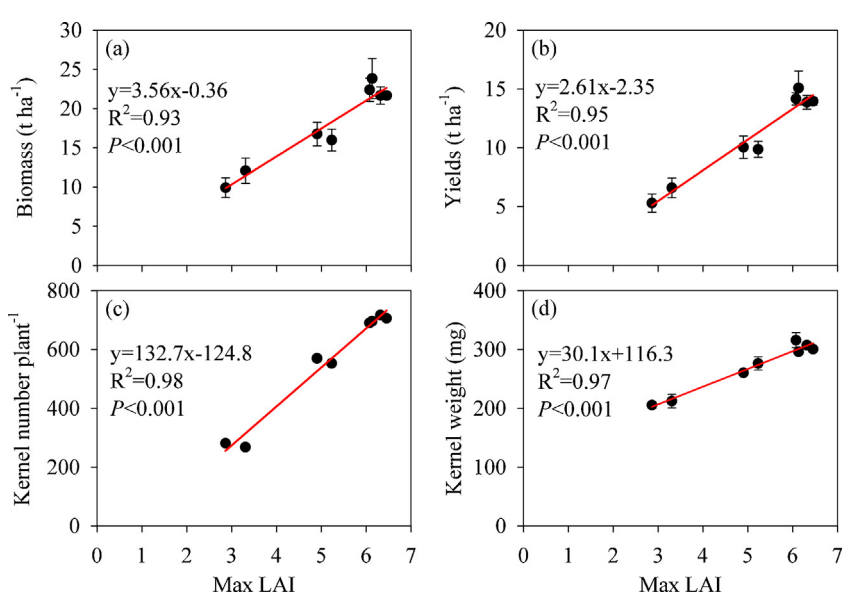

Fig. 8. The relationship between total biomass (a), grain yields (b), kernel number (c), kernel weight and maximum LAI of all treatments in both years.

that were obtained in this work show that maize grain yields of $14.9 \pm 1.3\,t\,ha^{-1}$ (in 2007) can be achieved under plastic film mulching conditions. The higher yield was primarily due to the higher N fertiliser ($280\,kg\,N\,ha^{-1}$) and to greater heat resources; in particular, the topsoil temperature was improved by plastic film mulching. However, in the rainless (<300 mm) western region of the Loess Plateau, the maize grain yield was only $6.1\,t\,ha^{-1}$ under plastic film mulching conditions (Zhou et al., 2009). The lower grain yield was achieved primarily due to the limited water supply.

The importance of N nutrition as the most limiting factor in maize growth is well-known. Binder et al. (2000) found that the N deficit limitation on plant growth depends on the degree of N deficiency during the initial growth periods. The primary reason for this observation is that early N stress strongly diminished leaf expansion rate and leaf area duration (Wolfe et al., 1988) and reduced subsequent radiation interception (Uhart and Andrade, 1995). Our results indicated that N stress significantly decreased leaf growth during the VS stage, which resulted in only 20–50% of the simulated potential LAI in the N0 treatment. This rapid leaf senescence was also found in the N stress plots during the RS stage. N application significantly improved the leaf expansion during the initial growth stages (before and during silking phase), which resulted in 60–70% of the simulated potential LAI in the N100 treatment or achieved 100% of the simulated potential LAI in the N250 and N400 treatments. The significant prolonged leaf area duration and higher LAI values in the N application plots was due to the sufficient N supply during later growth stages.

Crop biomass production and, particularly, the grain yield were directly associated with the current rates of assimilation and translocation during the RS period (Chen et al., 2003). Uhart and Andrade (1995) documented that a N deficit could reduce the dry matter partitioning to reproductive sinks at the flowering stage of maize. Our results showed that significantly more dry matter accumulation was formed during the RS period with increasing application rates of N fertilisers from 0 to $250\,kg\,ha^{-1}$. Meanwhile the allocation and the achievement of the simulated potential of dry matter increased significantly during the RS period. The factors that improved crop productivity consistently resulted in significantly higher LAI values following the application of increasing doses of N fertiliser. In particular, leaf senescence was significantly delayed during the RS stage. These results indicated that the reduction in maize productivity under N nutrition stress is primarily due to lower LAI values during the VS period and to the reduced longevity of leaves during the RS period.

The dry matter accumulation in maize kernels begins shortly after fertilisation and progresses in a sigmoidal pattern that includes a lag phase, where the sink capacity is set (Jones et al., 1996), a linear growth phase, which is also known as the effective grain filling period (Westgate et al., 2004), and a quiescent state, where the kernels achieve the maximum dry weight. This final stage is called physiological maturity (Saini and Westgate, 2000). The final kernel weight is determined by the kernel growth rate during the effective grain filling period (Borrás et al., 2003) and by the duration of this period (Echarte et al., 2006; Sala et al., 2007). The kernel growth rate and the duration of the grain filling period are determined by the source – sink co-limitation (Borrás and Otegui, 2001). Mayer et al. (2012) documented that maize kernel weight may increase in response to high N supply, which is related to the duration of the effective grain filling period. This study indicated that the higher N fertiliser treatment resulted in a greater leaf and canopy growth and maintained a higher source capacity during the grain filling period, which thus provided sufficient assimilation products to fulfil the potential requirements of the higher kernel growth rate and longer grain filling period. However, the N stress treatment decreased the LAI and canopy growth, which thereby decreased the kernel growth rate and the duration of the grain filling period, resulting in lower final kernel weights in each region of the ear.

Generally, both the kernel number and weight determine the final grain yield of maize. Variations in the grain yield are commonly explained by variations in the kernel number, which has been strongly correlated with traits that are responsible for plant biomass production (Andrade et al., 2002). Jones et al. (1996) found that the kernel number, which is established during the lag phase when the sink capacity is set, was primarily determined by resource limitations at the flowering stage (Gambín and Borrás, 2010). Previous results have demonstrated the importance of both photo-assimilation and N availability on maize kernel number determination during the critical period for kernel set (D'Andrea et al., 2008). The current study consistently found that the kernel numbers significantly increased with the increasing application rates of N fertiliser; this increase in the kernel number is primarily due to the larger LAI and to the robust plant growth, which leads to greater dry matter assimilation around the flowering stage. N stress significantly decreased the LAI and biomass production, which thereby decreased the source capacity during the grain establishing process, resulting in lower final kernel numbers.

Mueller et al. (2012) estimated that closing the yield gaps and achieving 100% of the attainable yields could increase worldwide crop production by 64% for maize. Notably, closing maize yield gaps to 50% of attainable yields primarily requires addressing nutrient deficiencies; however, closing yield gaps to 75% of attainable yields requires increases in both water supply and in nutrient application over most of the region (Mueller et al., 2012). For dryland farming in northwest China, the maize yield gap was greater than 50%, and closing the yield gap was primarily controlled by the water shortage and by N nutrient limitations (Zhou et al., 2009; Ju et al., 2009). Using the FM module of the Hybrid-Maize model, which was combined with field experiments using different levels of N fertiliser, we found that maize achieved only 40–50% of the simulated potential yield in the N0 treatment and 70–80% of the simulated potential yield in the N100 treatment. The higher achievement of the simulated potential in N stress conditions may be due to the plastic film mulching in both wet years, which effectively solved the water shortage problem (2010 and 2011). The application of $250\,kg\,ha^{-1}$ N fertiliser could fully satisfy this nutritional requirement during the entire growth season of maize and allow the crop to reach 100% of the simulated potential productivity. Although more N fertiliser was added in other trials, the application of $400\,kg\,ha^{-1}$ N fertiliser did not increase productivity and even decreased this productivity. This result was presumably because excessive N fertiliser resulted in plant lodging during the RS period, although single plant productivity improved.

5. Conclusions

Field testing indicated that the new FM module of the Hybrid-Maize model could accurately estimate maize plant growth and grain yield under a plastic film mulching condition. Using the FM module of the Hybrid-Maize model, which was combined with field experiments using different levels of N fertiliser, we found that the N stress treatment has significantly limited canopy growth and decreased the achievement of the simulated potential productivity. N fertilisation accelerated LAI growth, which thereby increased dry matter accumulation, resulting in greater allocation during the reproductive stage. Meanwhile, N fertilisation induced greater grain numbers and larger kernel weights, which were primarily due to the greater grain filling rate and longer duration; therefore, the grain yield significantly improved, and the attainable productivity was achieved.

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