Response of Soybean Yield to Daytime Temperature Change during Seed Filling: A Long-Term Field Study in Northeast China

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Abstract: Daytime temperature during seed filling is a crucial determinant of grain yield in pulse crops. Although there is much research about the effect of daytime temperature during seed filling on soybean yield in temperature-controlled chambers, the effect in the field has been little explored. Long-term manipulative field experiments are important tools to provide accurate information for revealing the impacts of climate change on crop yields. Using the field records of a long-term fertilization experiment conducted in Northeast China, we analyzed the response of soybean yields to mean daily maximum temperature during seed filling over the period 1987-2007. The results showed that there was a clear positive response of soybean yields to increased mean daily maximum temperature during seed filling ranged from 20 to 24ºC. When compared with the average soybean yields over the last two decades, grain yields increased by 6-10% for each 1ºC increase in mean daily maximum temperature during seed filling and more than 22% of yield trends can be explained. These findings provide a direct evidence for the response of soybean yield to climate change in the field study.

Key words: Adaptation, Climate change, Daytime temperature, Food security, Long-term experiment, Seed filling, Soybean, Yield.

First domesticated in Northeast China, soybean has become the major food crop for humans and high protein feed supplements for livestock all over the world. In 2005, Northeast China planted more than 4 million ha of soybean and produced 7.98 million Mg of grain, which contribute to 37% and 48.8%, respectively, of the nation’s total (Editorial Board for Agricultural Yearbook of China, 2006). Soybean production is extremely important to the economy of Northeast China, which is largely based on weather-sensitive agricultural production systems.

There is now ample evidence that crop yields and food security will be influenced negatively by temperature increases in many parts of the world (Peng et al., 2004; Easterling et al., 2007; Lobell et al., 2004; Tao et al., 2008). Indeed, previous studies have investigated the effects of increased temperature on soybean yield. Crop modeling studies suggested that there would be a decrease in soybean yield in some future climate scenarios in India when the effect of rise in surface air temperature was considered (Lal et al., 1999; Mall et al., 2004). Empirical analysis revealed that growing season temperature had a negative impact on soybean yields at many locations in the United States and there was an average of 17% reduction in yield for every 1ºC rise (Lobell and Asner, 2003). However, these studies mainly focused on the effects of increases in temperature during the entire life cycle of soybean and the influence of temperature during growth stages has received little consideration.

Seed filling is the most important stage determining soybean yield. During this stage, grain growth enters a linear phase and most of grain mass accumulates. Environmental conditions, particularly daytime temperature, have a direct effect on soybean yield. This is because processes such as photosynthesis and transpiration are concentrated in daytime. Some reports have demonstrated that soybean crops are more responsive to daily maximum temperature (Gibson and Mullen, 1996; Lal et al., 1999). Anthropogenic global warming is no longer a hypothesis (Trenberth et al., 2007) and this warming has been characterized by large increase in daily maximum temperature (Vose et al., 2005). The linear trend in daily maximum temperature over global land-surface since 1979 (0.29ºC decade\(^{-1}\)) is double that over the last 50 years (0.14ºC decade\(^{-1}\)) (Vose et al., 2005). In order to adapt soybean systems to the increased daytime temperature, a comprehensive understanding of the impact during seed filling on soybean yield is warranted. Controlled environment chambers have proven that moderate increase in daytime temperature (18–26ºC) during seed filling benefited soybean yield (Sionit et al., 1987), but soybean yield decreased as
daytime temperature increased above 26°C (Huxley et al., 1976; Dornbos and Mullen, 1991; Gibson and Mullen, 1996). In the controlled experiments, daytime temperatures were held constant during seed filling; in contrast, daily maximum temperature in the fields varies daily and gradually decreases during the period. Therefore, it is very difficult to extrapolate the results of temperature controlled experiments to the fields. Records of the long-term agrosystems provide a unique opportunity to evaluate the response of soybean yields to daily maximum temperature during seed filling in the fields. In this study, we aim to investigate how soybean yields respond to daily maximum temperature during seed filling in the field fertilization experiment.

Materials and Methods

1. Description of the long-term experiment

A long-term wheat-corn-soybean cropping system was established on a silty clay loam or silty clay in 1985 in Hailun Experimental Station of Agricultural Ecology (Heilongjiang, China, 47°26′N, 126°38′E), Chinese Academy of Sciences. The station receives 464 mm of rainfall annually since 1979, of which 80% occurs from June to September. The annual mean air temperature was 2.41°C during the period 1979-2007. The field is flat with an elevation of 240 m. Before treatments were established, the initial soil characteristics (0-20 cm layer) in the field were pH 6.2, soil organic matter 54.0 g kg⁻¹, total N 3.0 g kg⁻¹, available P 25.8 mg kg⁻¹, and available K 191 mg kg⁻¹ (Shen et al., 1998).

2. Experimental design and agronomic management

The experiment included three blocks for crop rotation with each crop present in each year. Eight fertilization treatments with three replications were established in each block, and each treatment covered 224 m² (40 × 5.6 m). The eight treatments were no fertilization applied (CK); only farmyard manure applied (FYM); only N applied (N); N and FYM applied (N+FYM); N and P applied (NP); N, P, and FYM applied (NP+FYM); N, P, and K applied (NPK); N, P, K, and FYM applied (NPK+FYM).

As Urea, P as Diammonium Hydrogen Phosphate, and K as Potassium Sulfate were applied. The annual dose of N, P, and K was the same in all the treatments with no adjustment to compensate for nutrients in the FYM. N was applied at a rate of 107.2 kg N ha⁻¹ for wheat and corn, but zero for soybean; P and K were applied at rates of 18.6 kg P ha⁻¹ and 60 kg K ha⁻¹, respectively. FYM is defined as follows: 80% of harvested grain from each treatment was fed to pigs, and stem was shredded into pieces and placed into the pig sties. The decomposed, mixed manure and residues were applied annually to the original plots where the grain and straw came from forming a closed system. The long-term experiment was also described in more detail by other researchers (Shen et al., 1998; Han et al., 2006).

Soybean was sown in the early May in a 0.65 m rows at a rate 55 kg ha⁻¹; corn and wheat were sown in the early May and April, respectively. Cultivars of soybean (Glycine max (L.) Merr.), corn (Zea mays L.) and wheat (Triticum aestivum L.) were Heinong 35, Haiyu 6 and Long 4083 respectively, and the same cultivars were used in the treatments every year. Herbicides and pesticides were applied at the same rates in all the treatments to control weeds and insects. There was no irrigation in any of the treatments during the study period.

3. Data collection

The daily weather data were recorded since 1952 at a Hailun meteorological station located about two kilometers from the long-term experiment site. Daily maximum temperature and precipitation data for Hailun meteorological station were obtained from the Chinese Meteorological Agency (http://data.cma.gov.cn/index.jsp). We extracted these climatic variables of growing season (from May to September) and seed filling over the period from 1987 to 2007. Average maximum temperature during the growing season and seed filling for each year was calculated as the mean of the daily maximum temperatures during the respective periods. Total precipitation during seed filling was computed for each year. The seed filling stage (R5 to R7) was determined by the soybean phenomenology staging system developed by Fehr and Caviness (1977) and started roughly in the middle of August.

At soybean maturity, samples of all the treatment plots were harvested from a 1 m² (1×1m) harvest area for each replication. The grain was separated from the stem and dry weight of the grain was determined after oven drying at 70°C to constant weight. Soybean grain yield was adjusted to a water content of 12.5% wet weight. We used the average of soybean yield from the three replicates for each fertilization treatment in each year as the dependent variable in subsequent analyses.

4. Statistical analysis

All statistical analyses were performed by SYSTAT 12.
The significance of time trends in changes of soybean yield and maximum temperature were analyzed by using the Student's t test. We used a common approach (Nicholls, 1997; Lobell and Field, 2007) to account for long-term trends in soybean yield caused by changes in climatic variables. This approach calculated annual year-to-year changes in each variable. A first-difference time series for yield and climatic variables was used to remove the possible influences of non-climatic factors such as crop management. Stepwise multiple linear regressions were then performed with first differences in yields ($\Delta$Yield) as the response variables, and first differences of average maximum temperature ($\Delta T_{\text{max}}$) and precipitation ($\Delta P$) during seed filling as predictor variables. The linear regression model is given by:

$$\Delta \text{Yield} = \alpha + \delta_A \Delta T_{\text{max}} + \delta_B \Delta P + \epsilon$$  \hspace{1cm} [1]

where $\Delta \text{Yield}$ represents the change in yield; $\Delta T_{\text{max}}$ is the change in average maximum temperature during seed filling (°C); $\Delta P$ is the change in precipitation (mm) during seed filling; $\alpha$ is the model intercept, $\delta$'s are the coefficients for each climatic variable, and $\epsilon$ is the model error.

### Results

#### 1. Daytime temperature

Mean daily maximum temperature during the seed filling period ranged from 20 to 24°C over the period 1987–2007, which was about 2°C lower than that during all the growing season (P<0.01). On average, the mean daily maximum temperature during the seed filling period and growing season increased by 1.14°C and 0.82°C per decade, respectively. The rates of warming are almost triple that of annual mean land surface in the Northern hemisphere from 1979 to 2005 (0.29 to 0.33°C per decade) (Trenberth et al., 2007).

Fig. 2. Soybean yields for different fertilization treatments from 1987 to 2007.

CK; no fertilization applied treatment, FYM; only farmyard manure applied treatment, N; only N applied treatment, N+FYM; N and FYM applied treatment, NP; N and P applied treatment, NP+FYM; N, P, and FYM applied treatment, NPK, N, P and K applied treatment, NPK+FYM; N, P, K, and FYM applied treatment.
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2. Soybean yield and yield trends

Soybean grain yields in each treatment from 1987 to 2007 were illustrated in Fig. 2. Mean soybean yields ranged from 189 g m$^{-2}$ in the CK treatment to 218 g m$^{-2}$ in the NPK + FYM treatment. The linear regressions of yields versus time had positive slopes and were significant ($P < 0.05$) in all treatments except the CK and N treatments. The largest trend (+ 4.57 g m$^{-2}$ yr$^{-1}$) occurred in the NPK + FYM treatment (Fig. 2). Rapid increases in soybean yield indicate that soybean yield stagnation in Northeast China may have not been reached through 2007. Egli (2008) also reported that there was no convincing evidence that soybean yields are reaching plateaus in productive environments in mid-western USA.

The application of FYM accelerated the trend of increasing soybean yields over time compared with the corresponding fertilizer treatment without FYM (i.e. larger slopes for FYM) (Fig. 2). The results indicate that FYM had residual effects and gradually improved soil productivity resulting in increased soybean yields over the duration of experiment. This finding was in agreement with increased yield for three crops in rotation (including soybean) in Northeast China reported by other researchers (Zhang et al., 2000; Liu et al., 2001). Other studies also reported that FYM application to rice field showed significant residual effects in the following wheat crop in India (Yadvinder et al., 2004).

3. Relationships of soybean yields and daytime temperature

The results of multivariate linear regression analysis for soybean yield and seed filling climatic variables are shown in Table 1. We found strong relationships between changes in mean daily maximum temperature during seed filling and soybean yields under different fertilization treatments since 1987. Among the eight fertilization treatments, the estimates of regression models revealed significant positive responses of soybean yields to daytime temperature during seed filling ($P < 0.05$), except for the CK and N treatments (Table 1). The regression analysis showed that changes in grain yields from year to year for all the fertilization treatments was not related to variation of precipitation during seed filling ($P > 0.05$). In order to further investigate the singular importance of daytime temperature, we developed a simple linear regression between the first differences (year-to-year change) of soybean yield and average maximum temperature during seed filling (Fig. 3). Our results indicate that at least 22% of the variation in year-to-year yield changes could be explained by average maximum temperature warming during seed filling. In NP + FYM and NPK + FYM treatments, more than 30% of yield variability was attributed to average maximum temperature during seed filling. The resulting coefficients from the regression analysis suggest that soybean grain yield increased by roughly 6–10% for each 1°C increase in daytime temperature during seed filling when compared with the average soybean yield for each treatment during the period 1987–2007 (Fig. 4).

Discussion

The present study revealed that elevated mean daily maximum temperature during seed filling has had a discernible positive impact on soybean

| Treatment | Variable | Estimate | S.E. | P   | Model $R^2$ |
|-----------|----------|----------|------|-----|-------------|
| CK        | $\Delta T_{\text{max}}$ | 4.45     | 3.60 | 0.23 | 0.09        |
|           | $\Delta P$ | -0.07    | 0.12 | 0.54 |             |
| FYM       | $\Delta T_{\text{max}}$ | 8.30     | 3.63 | 0.04 | 0.25        |
|           | $\Delta P$ | -0.10    | 0.12 | 0.39 |             |
| N         | $\Delta T_{\text{max}}$ | 15.07    | 6.05 | 0.02 | 0.31        |
|           | $\Delta P$ | -0.30    | 0.20 | 0.15 |             |
| N + FYM   | $\Delta T_{\text{max}}$ | 14.63    | 4.22 | < 0.01 | 0.47       |
|           | $\Delta P$ | -0.30    | 0.14 | 0.06 |             |
| NP        | $\Delta T_{\text{max}}$ | 13.65    | 5.00 | 0.01 | 0.31        |
|           | $\Delta P$ | -0.14    | 0.16 | 0.40 |             |
| NP + FYM  | $\Delta T_{\text{max}}$ | 13.90    | 4.10 | < 0.01 | 0.42       |
|           | $\Delta P$ | -0.17    | 0.13 | 0.22 |             |
| NPK       | $\Delta T_{\text{max}}$ | 10.81    | 5.99 | 0.09 | 0.21        |
|           | $\Delta P$ | -0.27    | 0.20 | 0.18 |             |
| NPK + FYM | $\Delta T_{\text{max}}$ | 14.75    | 4.98 | < 0.01 | 0.36       |
|           | $\Delta P$ | -0.20    | 0.16 | 0.24 |             |
yield. The results agree with the findings of the controlled environment studies that soybean seed yield increases as daily maximum temperature during seed development increases in cooler regions (Huxley et al., 1976; Sionit et al., 1987; Pan, 1996). At Hailun agroecosystem experiment station, the mean daily maximum temperature during seed filling varied from 20 to 24ºC over the study period which is within the maximum temperature range (18 to 30ºC) that gave maximum grain yield as found in the above studies. Since grain yield of soybean is a function of duration and rate of grain filling, abiotic effects, particularly daily maximum temperature and water, during the grain filling period would have a direct effect on grain yield. Previous studies showed that the seed filling rate increased as daily maximum temperature during seed filling increased from 18 to 27ºC (Egli and Wardlaw, 1980), but seed growth duration was insensitive to increases in daily maximum temperature between 20 and 30ºC (Egli and Wardlaw, 1980) and between 30 and 35ºC (Gibson and Mullen, 1996). This suggests that higher soybean yield resulting from the elevated daily maximum temperature in our study was primarily due to the increased seed filling rate. Studies on the contribution of seed filling duration and rate to grain yield in rice and maize also showed that grain weight was mainly determined by the seed filling rate (Jones et

Fig. 3. Relationships between first-differences (year-to-year changes) of yield and first-differences of average maximum temperature during seed filling. Scatter plots labeled with the lines of estimates (solid lines) and 95% prediction intervals (dashed lines) are statistically significant at P=0.05.

CK; no fertilization applied treatment, FYM; only farmyard manure applied treatment, N; only N applied treatment, N+FYM; N and FYM applied treatment, NP; N and P applied treatment, NP+FYM; N, P, and FYM applied treatment, NPK; N, P, and K applied treatment, NPK+FYM; N, P, K, and FYM applied treatment.

Fig. 4. The changes in soybean yields for each degree increase in maximum temperature during seed filling when compared with the average soybean yield for each treatment over 1987–2007 (n=20 for each treatment). CK; no fertilization applied treatment, FYM; only farmyard manure applied treatment, N; only N applied treatment, N+FYM; N and FYM applied treatment, NP; N and P applied treatment, NP+FYM; N, P, and FYM applied treatment, NPK; N, P, and K applied treatment, NPK+FYM; N, P, K, and FYM applied treatment. "ns" indicates no significant yield impact at P=0.05. Error bars show the 95% confidence intervals.
al., 1979; Wang et al., 1999). In terms of precipitation, Brevened and Egli (2003) found that a short period of water stress during seed filling induced acceleration of leaf senescence and shortened the duration of seed filling and led to reductions in soybean yield. According to the present study, there was no significant relationship between soybean yield and precipitation during seed filling (Table 1). This indicates that water stress during seed filling did not occur in this rainfed area. Overall, our results highlight the important contribution of daily maximum temperature during seed filling to soybean yield. Increasing daily maximum temperature during seed filling, associated with global warming will likely continue benefit soybean yield in the study region for a few decades.

However, an excessively high day temperature during seed filling of soybean has a negative impact on grain yield. Dornbos and Mullen (1991) reported that maximum day temperatures from 29 to 34°C during seed filling period combined with a constant night temperature of 20°C decreased soybean yield. An increase in maximum temperature from 30 to 35°C during seed filling resulted in an 15% and 18% decrease in weight per seed and the final seed weight per plant, respectively (Gibson and Mullen, 1996). Effects decreased seed growth rates were found at maximum daytime temperature over 30°C (Egli and Wardlaw, 1980; Gibson and Mullen, 1996). Predictions from mechanistic and empirical models showed that a rise in surface air temperature during growing season would severely reduce soybean grain yield (Lal et al., 1999; Lobell and Asner, 2003; Mall et al., 2004). In central India, soybean yields were found to be more vulnerable to an increase in maximum temperature than decrease in minimum temperature (Lal et al., 1999). These results suggest that the impact of increased temperature, especially daytime temperature, will be a big challenge to sustainability of the soybean cropping system in the future.

Concerns about agricultural adaptation options to climate change have motivated an influential research program on sustainable agriculture (Howden et al., 2007; Naylor et al., 2007). For example, some studies have established the effective adaptation options which include use of conservation tillage, changing varieties (Howden et al., 2007), changes in planting date (Mall et al., 2004; Easterling et al., 2007; Kucharik, 2008) and conversion from rain-fed to irrigated condition (Easterling et al., 2007). In this respect, the results presented above suggest that soybean yield appears to benefit more from earlier occurrence of seed filling because surface air temperature begins to decline in the study area when seed filling period in soybean starts. Adaptation to this environmental factor could be achieved by means of advancement in biotechnology and agronomic management. On the other hand, with the rapid increase of temperature during seed filling, the threshold of optimum daytime temperature for growth and development in soybean may be exceeded in the study area in a few decades. This would result in a decrease in soybean grain yield. In addition, high temperature will accelerate the occurrence of drought conditions for soybean. It has been commonly accepted that drought shortens the duration of seed filling for soybean, which also decreases soybean yields (Egli, 2004). All these negative impacts on grain yield indicate a pressing need for developing more strategies (e.g., introduction of genotypes with drought-tolerance) for adapting soybean systems in Northeast China to climate change.

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