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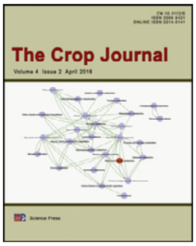

Warming decreases photosynthates and yield of soybean [*Glycine max* (L.) Merrill] in the North China Plain

Lixia Zhang[*], *Lili Zhu*, *Mengyang Yu*, *Mingxing Zhong*

State Key Laboratory of Cotton Biology, Key Laboratory of Plant Stress Biology, College of Life Sciences, Henan University, Kaifeng 475004, China

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ABSTRACT

Understanding the responses of field crops such as soybean to climate warming is critical for economic development and adaptive management of food security. A field warming experiment was conducted using infrared heaters to investigate the responses of soybean phenology, photosynthetic characteristics, and yield to climate warming in the North China Plain. The results showed that 0.4 °C and 0.7 °C increases in soybean canopy air and soil temperature advanced anthesis stage by 3.8 days and shortened the length of entire growth stage by 4.5 days. Warming also decreased the leaf photosynthetic rate by 6.6% and 10.3% at the anthesis and seed filling stages, respectively, but increased the leaf vapor pressure deficit by 9.4%, 15.7%, and 14.1% at the anthesis, pod setting, and seed filling stages, respectively. However, leaf soluble sugar and starch were decreased by 25.6% and 20.5%, respectively, whereas stem soluble sugar was reduced by 12.2% at the anthesis stage under experimental warming. The transportation amount of leaf soluble sugar and contribution rate of transportation amount to seed weight were reduced by 58.2% and 7.7%, respectively, under warming. As a result, warming significantly decreased 100-seed weight and soybean yield by 20.8% and 45.0%, respectively. Our findings provide better mechanistic understanding of soybean yield response to climate warming and could be helpful for forecasting soybean yield under future climate warming conditions.

1. Introduction

Global mean air temperature has increased by about 0.74 °C over the last century and is predicted to increase by 1.1 to 6.4 °C by the end of this century [1]. Changes in temperature have profoundly affected crop growth, development, and yield. Most studies of crops (such as wheat, rice, and maize) have found that climate warming could affect crop phenology [2–4], spikelet sterility [5,6], photosynthesis and carbon metabolism [7–10], yield, and quality [11–15]. As the most widely grown legume, soybean is a major source of plant protein and oil and has become an important commodity crop in the word. Future demand for soybean will continue to increase due to world population increase, dietary change, and edible oil demand [16]. Better understanding of responses of soybean growth and yield to climate warming will facilitate strategy development for future food security.

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[*] *Corresponding author*. Tel.: +86 371 23881006; fax: +86 371 23882029.
E-mail address: zhanglixia_1010@163.com (L. Zhang).
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The effects of warming on soybean yield have been investigated mostly using crop models and historical data analyses. For example, crop model studies have suggested that soybean yield is negatively correlated with growing season warming [12,17,18]. Empirical analysis has indicated that warming could decrease soybean yield and that there is an average of 17% reduction in soybean yield for every 1 °C rise in temperature [19]. However, most studies using controlled chambers and greenhouses have found that warming might stimulate soybean yield in a certain temperature range [20] but would reduce yield above the temperature threshold during the seed filling stage [21,22]. Thus, responses of soybean yield to warming remain elusive. Most studies have indicated warming-induced increase and/or decrease in crop yield due to changes in phenological stage [23,24] and leaf photosynthetic characteristics [25,26], improvement in sources (leaf area and photosynthesis), and changes in sinks size (number of flowers, pods, seeds, and seed weight) [27,28]. Warming during reproductive growth might also influence pollen or stigma viability, pollen tube growth, and flower fertilization, finally leading to changes in soybean yield [29]. These studies have shown that the underlying mechanisms of warming effects on soybean yield remain complex. It is thus imperative to characterize the actual response of soybean yield to climate warming.

Soybean is one of the major crops in the North China Plain. To date, no field warming experiment has been performed in this region. A warming experiment with infrared heaters was conducted to investigate the responses of soybean phenology, photosynthetic characteristics, and yield to climate warming. The main objectives of this study were 1) to determine the extent to which warming affects soybean photosynthates and yield and 2) to identify the mechanisms responsible for reduction in soybean yield under climate warming.

2. Materials and methods

2.1. Study site

The study was conducted on the on-campus Research and Educational Farm (34°49′N, 114°17′E, 73 m.a.s.l.) of Henan University, Kaifeng, Henan province, China, in 2013. The area has a typical temperate arid climate. Mean annual air temperature is 14.3 °C, with monthly mean temperature ranging from −0.16 °C in January to 27.2 °C in July in the past 60 years (1953–2013) (temperature data were obtained from the Chinese Meteorological Agency, http://cdc.cma.gov.cn/home.do). Mean annual precipitation is 627 mm, of which 87.8% are distributed from April to October. Soil parent material and type are Yellow River sediment and sandy loam, respectively, with 65.7 ± 0.15% sand, 14.1 ± 0.03% silt, and 20.30 ± 0.02% clay. The sandy loam soils contain 11.04 ± 0.16 g kg^{-1} soil organic carbon, 0.47 ±0.01 g kg^{-1} total nitrogen, and 27.20 ± 1.21 mg kg^{-1} dissolved organic nitrogen. Soil bulk density is 1.31 g cm^{-3} and soil pH is 8.66.

2.2. Experimental design and agronomic management

The field experiment used a complete randomized block design with two treatments, including ambient temperature as a control (C) and a diurnal warming treatment (W), replicated 6 times per treatment. Twelve plots (3 × 4 m in each plot) were arranged into three rows and four columns. There was 1 m-wide buffer zone between any two plots. In each warming plot, an infrared radiator (165 × 15 cm, Kalglo Electronics, Bethlehem, PA, USA) was suspended 2.25 m above the ground. The heater for the warming treatment was set at a radiation output of approximately 1600 W. This heater can provide about 10 m^2 warming area with uniform and reliable warming effects, as reported in the previous study [30]. A dummy heater of the same shape and size was used to mimic the shading effect of the infrared heater in each control plot. The warming treatment was begun on the sowing date and maintained until the harvest date for an entire growing season. All plant samples and field measurements were performed in the approximate 10 m^2 area in each plot.

Soybean seed (cv. Zhonghuang 13) was obtained from a local seed company and sown on June 1. After seedlings emerged in 5 days, plants were thinned to a density of 24 plants per m^2. Herbicides and pesticides were applied as necessary, following local agronomic management practices. Irrigation was generally performed at the anthesis and seed filling stages according to soybean growth demand. Soybeans were harvested on October 6.

2.3. Field measurements

2.3.1. Temperature and moisture

Plant canopy air temperature (Tc) and soil temperature (Ts) were measured with a thermocouple and recorded with automatic data loggers, respectively (Ibutton, DS1922L-F50). Two temperature sensors were placed at the center of each plot. One sensor was positioned in the soybean canopy for air temperature measurement and was gradually raised with the soybean growth. The other sensor was buried 10 cm below the soil surface for soil temperature measurement. The temperature data were stored at 1 h intervals for the entire growing stage. Soil moisture at the depth of 0–10 cm was measured using TDR (this instrument was produced by Sentek Pty Ltd., Balmain, Australia), recorded 6 times per month from June to October in each plot.

2.3.2. Soybean phenophase, biomass growth, and grain yield

The phenological stages of soybean include both vegetative (V1–Vn) and reproductive (R1–R8) development stages. The dates of the developmental stages were recorded for each plot, based on the method of a previous study [31]. The entire growing stages of soybean were divided into pre-anthesis and post-anthesis stages. Anthesis, pod setting, seed filling, and maturity stages were defined, respectively, as the times when 50% of plants flowered, pods set, seeds filled, and pods and leaves showed yellow color in each plot.

At the harvest stage, five plant samples were taken from each plot to measure aboveground biomass (AGB). Soybean yield was determined by harvesting a 1 m^2 area from each plot by hand. The pod tissues were passed through a thresher to separate the seeds, which were weighed to obtain seed yield (SY). All plant samples were oven-dried at 65 °C for 24 h and weighed. The harvest index (HI) was calculated as HI = SY/AGB.