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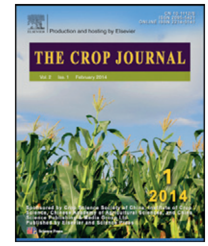

Impacts of nighttime post-anthesis warming on rice productivity and grain quality in East China

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ABSTRACT

The impacts of nighttime post-anthesis warming on rice productivity and grain quality in East China were evaluated for two cultivars, II You 128, an *indica* rice, and Wuyunjing 7, a *japonica* rice. Warming by 3.0 °C stimulated the nighttime respiration rate and decreased the photosynthesis rate, resulting in significant decreases of 21.2% and 24.9% in aboveground biomass accumulation for II You 128 and Wuyunjing 7, respectively. Warming significantly reduced the rates of seed setting and grain filling, especially of inferior kernels (those lower in panicles), while the filling rate of superior kernels remained almost unchanged. As a result, 1000-grain weight and grain yield were respectively 3.7% and 30.0% lower for II You 128 and 12.8% and 34.3% for Wuyunjing 7 in warmed plots than in the unwarmed control. Nighttime warming also significantly reduced the grain milling and appearance quality of both varieties. More negative effects of warming on inferior than on superior kernels were found. The above results have important implications for rice variety cultivation in East China.

1. Introduction

Global mean air temperature has increased by about 0.74 °C during the past 100 years, and is predicted to increase by 2.0–5.4 °C by the end of 2100 [1]. The elevation in the daily minimum temperature has been and will remain greater than that of the daily maximum temperature [2]. An average annual increase in grain production of 44 million metric tons is required to meet worldwide food demands by 2050 [3,4]. Given that temperature is a key factor determining crop yield and quality, the anticipated warming may strongly affect future food security [5,6]. Rice is one of the most important crops and a primary food source for more than half of the world's population, and more than 90% of the world's rice is produced and consumed in Asia [7]. Thus, quantifying the impact of daily minimum temperature elevation on rice growth in Asia may assist in developing strategies for cropping adaptation to future climatic warming.

Many uncertainties remain in the quantification of warming impacts on rice production, owing to insufficient understanding

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of rice growth response to the predicted warming [8]. For example, some studies have found that warming could enhance crop photosynthesis rate through a respiration-driven reduction in leaf carbohydrate concentration, likely resulting in unchanged biomass production [9]. Other studies have demonstrated that warming reduced the leaf photosynthesis rate and stimulated the night respiration rate, resulting in significant decreases in crop biomass production [10]. Most previous warming experiments have been conducted with an all-day warming regime, though the known and predicted elevations of the daily minimum temperature are higher than those of the daily maximum temperature. Warming at daytime or at nighttime can cause great differences in diurnal temperature range (DTR), which in turn will result in different impacts on crop growth and yield formation [11]. Thus, the evidence from previous warming experiments may not fully represent the actual responses of rice growth to the anticipated warming. In addition, warming-induced heat stress of rice growth occurs frequently during the post-anthesis phase, suggesting that post-anthesis warming at nighttime may occur more frequently and have greater impacts on rice production. Accordingly, it is desirable to quantify rice growth responses to nighttime post-anthesis warming.

East China is one of the most important rice cropping areas in Asia, and is predicted to warm by about 2.2 °C over the next 50 years with a faster nighttime than daytime increase [12]. In the present study, we conducted a warming experiment in Nanjing, Jiangsu province, China. Our objectives were to investigate the responses of rice growth and grain quality to nighttime warming during the post-anthesis phase.

2. Materials and methods

A pot culture experiment was conducted on the campus of Nanjing Agricultural University, Nanjing, Jiangsu province, China (32 02′ N, 118 52′ E, and 11 m a.s.l.) in 2010. The campus is located in the northern subtropical monsoon climate region. This experiment involved two treatments: post-anthesis warming at nighttime and an unwarmed control. Two leading cultivars, II You 128 (*indica* rice) and Wuyunjing 7 (*japonica* rice), were tested. There were 30 pots for each treatment of each variety.

The plastic pots were 25.0 cm in inside diameter, 22.0 cm in height, and 0.2 cm in thickness. Each pot contained 7.5 kg of dry brunisolic soil (Alfisol in USA-ST) with sand, silt, and clay proportions of respectively 0.5%, 75.3% and 24.2%. The soil was collected from the plow layer (0–20 cm) of a rice field at the Nanjing experiment station, Nanjing Agricultural University. Other properties of this soil were as follows: total N 2.52 g kg^{-1}, total P 0.60 g kg^{-1}, total K 14.00 g kg^{-1}, available P 166.22 mg kg^{-1}, available K 165.03 mg kg^{-1}, and soil organic C 8.24 g kg^{-1}.

The warming facility was a controlled-environment chamber (PQS-3, Southeast Instrument Co., Ltd., Ningbo, China), 4.5 m × 1.5 m × 1.7 m (length × width × height) in size. The air temperature and relative humidity in the chamber were controlled using electric resistance heaters and a bubbling system. The air temperature in the chamber at nighttime (19:00 to 7:00) was maintained at 25–28 °C with a wind speed of 0.5 m s^{-1}. The relative humidity was maintained at 75%–85%, similar to that of the unwarmed control environment. The air temperatures in the rice canopy in the chamber and the ambient environment were monitored every 10 min at night with a Thermo Recorder (ZDR-41, Zeda Instrument Co., Ltd., Hangzhou, China). The differences in rice canopy air temperatures at nighttime were automatically adjusted to approximately 3.0–3.5 °C higher in the chamber than in the ambient control environment (Fig. 1).

Germinated rice seeds were sown in plastic boxes on 13 May 2010. After one month of growth, rice seedlings were transplanted to the plastic pots. There were two holes seedlings for each pot and two seedlings for each hole. Fertilizer was applied as 0.75 g N, 0.38 g P_2O_5 and 0.38 g K_2O per pot. All of the P_2O_5 and K_2O and 50% of the N were applied as basal dressing. Half of the remaining N was applied as side dressing at the early tillering stage in the latter of June, and the rest of the N was applied at panicle initiation in the latter part of August. Water depth in all pots was maintained at about 5 cm above the soil surface during the entire rice growing cycle.

All pots were kept under ambient conditions outside the chamber before rice anthesis. During the post-anthesis phase, half of the pots were placed in the chamber for 12 h at night (from 19:00 to 7:00) and moved outside after 7:00 every day. The warmed and unwarmed pots were kept in the same ambient environment at the daytime from 7:00 to 19:00 every day during the post-anthesis phase.

At the anthesis and maturity stages, plants from three pots of each treatment were sampled and divided into leaf, stem, and panicle. All plant samples were oven-dried at 80 °C for 24 h and weighed. Post-anthesis biomass accumulation was calculated as the difference in total aboveground dry matter between the anthesis stage and harvest. Nine pots from each treatment were harvested to determine grain yield and its components.

At 0, 21 and 35 days post-anthesis (DPA), fifteen flag leaves of main stems were selected for measurements of net photosynthesis rate (from 9:00 to 11:00) and night respiration rate (from 22:00 to 23:00) with a portable photosynthesis system (Li-6400; Li-Cor, Inc., Lincoln, NE, USA). Another fifteen flag leaves were sampled in each treatment at 7, 14, 21, 28 and 35 DPA for measurements of chlorophyll a and b contents by the method of aqueous acetone extraction [13].

At the anthesis stage, approximately 200 rice panicles were labeled for the determination of grain filling rate. Fifteen panicles were taken from each treatment on 0, 7, 14, 21, 28 and 35 DPA. Kernels were stripped from panicles and divided into superior (those borne in the upper half of the panicle) and inferior (those borne in the lower half of the panicle) kernels [14]. All grain was oven-dried at 80 °C for 24 h and weighed.

After being harvested, rice grain was stored at room temperature for three months before quality testing. Grain milling and appearance quality indexes (brown rice, milled rice, head rice, and chalky grain proportions, chalkiness, and length–width ratio) were determined according to the National Standard of China, High Quality Paddy, GB/T 17891-1999.