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Yield formation of CO_2-enriched inter-subspecific hybrid rice cultivar Liangyoupeijiu under fully open-air field condition in a warm sub-tropical climate

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ABSTRACT

Hybrid rice (*Oryza sativa* L.) cultivars play an important role in rice production due to its heterosis, resistance to environmental stress and high yield potential. However, no attention has been given to its yield responses to rising atmospheric CO_2 concentration ([CO_2]). To address this need, we conducted a Free Air CO_2 Enrichment (FACE) experiment at Yangzhou, Jiangsu, China, in 2004–2006. A two-line inter-subspecific hybrid rice variety Liangyoupeijiu, recently bred in China, was grown at ambient or elevated (c. 570 μmol mol^{-1}) [CO_2] under two levels of nitrogen (N) application (12.5 and 25 g N m^{-2}). Elevated [CO_2] slightly accelerated phenological development (1–2 days), and substantially enhanced grain yield (+30%). The magnitude of yield response to [CO_2] was independent of N fertilization, but greatly varied among years. On average, elevated [CO_2] increased panicle number per unit land area by 8%, due to an increase in maximum tiller number under FACE, while productive tiller ratio remained unaffected. Spikelet number per panicle showed an average increase of 10% due to elevated [CO_2], which was also supported by increased plant height and dry weight per stem. Meanwhile, Elevated [CO_2] caused a significant enhancement in both filled spikelet percentage (+5%) and individual grain mass (+4%). Compared with previous rice FACE studies, this hybrid cultivar appears to profit much more from elevated [CO_2] than inbred japonica cultivars (c. +13%), not only due to its stronger sink generation, but also enhanced capacity to utilize the carbon sources in a high [CO_2] environment. As sufficient intraspecific variation in yield response exists under field conditions, there is a pressing need to identify genotypes which would produce maximum grain yield under projected future [CO_2] levels.

1. Introduction

Empirical records provide incontestable evidence of global changes; foremost among these changes is the increasing atmospheric [CO_2], which has risen from approx. 280 μmol mol^{-1} in pre-industrial times to approx. 370 μmol mol^{-1} now and may reach 570 μmol mol^{-1} by 2050 (IPCC, 2001). Rice (*Oryza sativa* L.) is unequivocally one of the most important food crops that feed the largest proportion of the world's population (Maclean et al., 2002). The demand for rice production will continue to increase in the coming decades, especially in the major rice-consuming countries of Asia, Africa and Latin America, due to the population explosion and cropland reduction. Accurate predictions of rice yield and of the ability of rice crops to adapt to high CO_2 environments are therefore crucial for understanding the impact of climate change on the future food supply.

As it is difficult to alter [CO_2] experimentally under open field condition, to date, most information on rice yield responses to elevated [CO_2] has been obtained from studies in enclosures, such as greenhouses (Imai et al., 1985; Ziska et al., 1996), Soil-Plant-Atmosphere research units (Baker and Allen, 1993), Temperature Gradient Chambers (Horie et al., 1995; Kim et al., 1996) and Open Top Chambers (Moya et al., 1998). However, these settings could cause substantial perturbation of the rice natural growing environment, which in combination with the edge effects associated with small plots, have been shown to modify the true responses of plants to increasing [CO_2] (McLeod and Long, 1999; Long et al., 2005). The Free Air CO_2 Enrichment (FACE) experiments, conducted in fully open-air field condition without altering microclimatic and biotic variables, represent our best simulations

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of the future high [CO_2] environment (Long et al., 2005). However, over the last decade, only two large-scale (12-m diameter) replicated rice FACE experiments have been conducted across the world (Okada et al., 2001; Liu et al., 2002). The first one commenced in 1998 in Shizukuishi, Iwate, Japan in a cool temperate climate (Kobayashi et al., 1999). In 2001, the second rice FACE system, which is also the longest running rice FACE experiment in the world, was set up in Jiangsu, China in a warm sub-tropical climate (Liu et al., 2002). Both experiments use the similar FACE technology and same target [CO_2] (570 μmol mol^{-1}) (Okada et al., 2001; Liu et al., 2002).

Quantification of genotypic variation in CO_2 response of rice yield and the basis for such variation is a crucial step in any effort to optimize yield with future higher atmospheric [CO_2]. However, to date, all elevated CO_2 experiments on rice yield have been conducted with inbred cultivars including japonica (Imai et al., 1985; Seneweera et al., 1996; Seneweera and Conroy, 1997; Kim et al., 2001, 2003a,b; Yang et al., 2006b) and indica type cultivars (Baker and Allen, 1993; Ziska et al., 1997; Moya et al., 1998). Because of its strong heterosis, enhanced resistance to environmental stresses and high yield potential, hybrid rice is widely used in China and accounts for more than 50% of the rice planted area in recent years (International Rice Research Institute, 2007). In particular, in order to further break the yield ceiling, China started a nationwide mega project for the development of "super" hybrid rice in 1996 (Cheng et al., 1998). This project aims to achieve a yield potential of 15 t ha^{-1} by 2015 and raise the national average rice yield to 7.5 t ha^{-1} by 2030 through the development of "super" hybrid rice varieties. Today, many "super" hybrid rice varieties have been released (Peng et al., 2004). However, to our knowledge, no previous studies have evaluated the yield responses of hybrid rice cultivars (include traditional and super hybrid rice varieties) to CO_2 enrichment.

Using a inbred japonica cultivar, the two previous works in the Japanese (1998–2000) and Chinese FACE studies (2001–2003) have investigated the effects of elevated [CO_2] and N supply on phenology (Kobayashi et al., 2001, 2006; Yang et al., 2007c), photosynthesis (Chen et al., 2005), growth (Kim et al., 2001, 2003b; Yang et al., 2006a), nutrient uptake (Yamakawa et al., 2004; Yang et al., 2007a,c), root development (Kim et al., 2003b; Yang et al., 2008), yield formation (Kim et al., 2001, 2003a; Yang et al., 2006b) and grain quality (Terao et al., 2005; Yang et al., 2007b). Compared with inbred rice cultivars, hybrid rice cultivars exhibit higher speed of tiller occurrence, thus relatively higher growth rate (Ling et al., 1994). Previous studies on C_3 species (other than rice) showed that potentially fast-growing species responded more strongly than slow-growing species (see reviews by Poorter, 1993). This factor suggests the likelihood of greater yield enhancement under elevated [CO_2] for hybrid vs. inbred type rice cultivars. In the current experiment, Liangyoupeijiu, a recently bred two-line (a single cross of two parental lines) 'super' hybrid rice variety, was examined under fully open-air conditions. The primary objective of this study was to evaluate the interactive effects of elevated [CO_2] and N availability on the yield and its components of hybrid rice, and to determine the consistency of the response over multiple growing seasons. No doubt, the results obtained here should provide further implications with respect to adaptation strategies of rice production under future elevated CO_2 conditions.

2. Materials and methods

2.1. Experiment site description and meteorology

As a part of the long-term FACE project in China, this study was conducted on a rice–wheat rotation field at Yangzhou city, Jiangsu province, China (32°35.5′N, 119°42′E), where the soil is classified as fluvisols (local name, Qingni soil). A rice–wheat rotation system prevails in this region. Relevant soil properties are as follows: soil organic C (SOC) 18.4 g kg^{-1}, total N 1.45 g kg^{-1}, total P 0.63 g kg^{-1}, total K 14.0 g kg^{-1}, available P 10.1 mg kg^{-1}, available K 70.5 mg kg^{-1}, and pH 7.2. The station, 5 m above sea level in elevation, sits in the subtropical marine climatic zone with mean annual precipitation being 980 mm, annual evaporation 1100 mm, annual mean temperature 14.9 °C annual sunshine hours 2100 h and frostless period 220 days.

2.2. FACE system

The China Rice FACE system has six plots located in different paddies having similar soils and agronomic histories. Three plots were randomly allocated for the elevated CO_2 treatments (hereinafter called E-[CO_2]) and three for the ambient treatments (hereinafter referred to as A-[CO_2]). In the E-[CO_2] plots, the plants were grown within 12 m diameter 'rings' in which pure CO_2 gas was released from peripheral emission tubes set 0.5 m above the canopy. A nominal usable area of each plot was ca. 80 m^2 with a 1 m buffer zone around the emission tubes. The A-[CO_2] plots had no ring structures, and the plants were grown in ambient [CO_2]. The target [CO_2] at the centre of the E-[CO_2] plots throughout the rice growth season was control to 200 μmol mol^{-1} above that of the A-[CO_2] plots. The actual season-long average [CO_2] for daylight hours (±S.E.) were 574 ± 39 (2004), 565 ± 39 (2005) and 564 ± 40 μmol mol^{-1} (2006) in the E-[CO_2] plots and 377 ± 21 μmol mol^{-1} (2004), 374 ± 21 μmol mol^{-1} (2005) and 378 ± 23 μmol mol^{-1} (2006) in the A-[CO_2] plots. Adjacent plots were buffered to avoid treatment cross-over. Details of the design, rationale, operation, and performance of the FACE system are provided by Okada et al. (2001) and Liu et al. (2002).

2.3. Crop cultivation

Liangyoupeijiu, a two-line hybrid variety of Peiai 64S × 9311 (Zou et al., 2003), was tested in this study. It is recently bred and one of the most popular 'super' hybrid rice variety in China (Peng et al., 2004). Standard cultivation practices as commonly performed in the area were followed in all experimental plots. Rice seeds were sown on 20 May. The seedlings grown under ambient air were manually transplanted at a density of one seedling hill^{-1} into the FACE and ambient plots on 15 June. Spacing of the hills was 16.7 by 25 cm (equivalent to 24 hills m^{-2}). Two levels of N were supplied as urea (N, 46.3%) and compound chemical fertilizer ($N:P_2O_5:K_2O$ = 15:15:15, %): low (LN, 12.5 g N m^{-2}) and high (HN, 25 g N m^{-2}). The planting area for Liangyoupeijiu in each N plot was 1 m^2 in 2004, and 8 m^2 in both 2005 and 2006. For two N levels, P and K were both applied as compound chemical fertilizer at equal rates of 7 g m^{-2}. N was applied as a basal dressing and as sidedressing at early-tillering (60% of the total) and at panicle initiation (PI) (40% of the total), while P or K was both applied as basal dressing. The rates and dates of N, P and K fertilizer applications are listed in Table 1. Mixing of paddy water between N treatments was minimized by separating the LN subplots from the rest of the plot (which received HN) with a 30 cm PVC barrier pushed 10 cm into the soil. The paddy fields were submerged with water, about 5 cm in depth, from 13 June to 10 July, drained dry several times from 11 July to 4 August, and then flooded with intermittent irrigation from 5 August to 10 days before harvest. The plants in both FACE and ambient plots were surrounded with border plants treated in the same way as the plants inside.