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Lodging in rice can be alleviated by atmospheric CO_2 enrichment

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Abstract

The projected increase of atmospheric CO_2 concentration [CO_2] is expected to increase yield of agricultural C_3 crops, but little is known about effects of [CO_2] on lodging that can reduce yield. This study examined the interaction between [CO_2] and nitrogen (N) fertilization on the lodging of rice (*Oryza sativa* L.) using free-air CO_2 enrichment (FACE) systems installed in paddy fields at Shizukuishi, Iwate, Japan (39°38′N, 140°57′E). Rice plants were grown under two levels of [CO_2] (ambient = 365 μmol mol^{-1}; elevated [CO_2] = 548 μmol mol^{-1}) and three N fertilization regimes: a single initial basal application of controlled-release urea (8 g N m^{-2}, CRN), split fertilization with a standard amount of ammonium sulfate (9 g N m^{-2}, MN), and ample N (15 g N m^{-2}, HN). Lodging score (six ranks at 18° intervals, with larger scores indicating greater bending), yield, and yield components were measured at maturity. The lodging score was significantly higher under HN than under CRN and MN, but lodging was alleviated by elevated [CO_2] under HN. This alleviation was associated with the shortened and thickened lower internodes, but was not associated with a change in the plant's mass moment around the culm base. A positively significant correlation between lodging score and ripening percentage indicated that ripening percentage decreased by 4.5% per one-unit increase in lodging score. These findings will be useful to develop functional algorithm that can be incorporated into mechanistic crop models to predict rice production more accurately in a changing climate and with different cultural practices.

Keywords: Free-air CO_2 enrichment (FACE); Lodging; Modeling; Nitrogen fertilization; Rice

1. Introduction

The projected increase of atmospheric CO_2 concentration [CO_2] is expected to enhance photosynthesis, thus resulting in increased growth and yield of many C_3 crops (Kimball et al., 2002), including rice (*Oryza sativa* L.). Rice, with an annual production of about 0.6 billion Mg and consumed mostly directly by humans, is the most important crop for feeding the world's population. In terms of world food security, it is essential to accurately predict rice production under future [CO_2] conditions. Researchers have reported a wide range of yield increases in response to elevated [CO_2], depending on the experimental conditions, but canopy-scale experiments have shown that [CO_2] increase of 200–300 μmol mol^{-1} can increase grain yield by 10–20% in non-stressed environments (Kim et al., 1996, 2003; Ziska et al., 1996). However, environmental stresses can interfere with various steps of the grain-formation processes and decrease

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yields (Yoshida, 1981). In particular, lodging can occur under heavy rains and strong winds, and this is a common problem that reduces rice yield (Hitaka and Kobayashi, 1961; Setter et al., 1997). Lodging decreases canopy photosynthesis due to self-shading (Setter et al., 1997) and disturbs the translocation of carbon and nutrients to the rice grains (Hitaka and Kobayashi, 1961), resulting in lower yield and poor grain quality. Setter et al. (1997) demonstrated that a moderate degree of lodging, which reduced canopy height by 35%, decreased yield by about 20%, and that severe lodging, which reduced canopy height by 75%, decreased yield by up to 50%. If elevated [CO_2] increases lodging, the yield gain due to the elevated [CO_2] could be nullified, and elevated [CO_2] could even decrease yield if the lodging is sufficiently severe. To predict future rice production and to policy determination efforts, the effects of [CO_2] on lodging must be evaluated.

Lodging is accelerated by heavier panicles and longer culms, which increases the plant's mass moment (mass multiplied by distance from the point of attachment). Elevated [CO_2] has been shown to increase the rate of grain filling and the final weight of the panicles as a result of increased panicle size (Kim et al., 2003; Baker, 2004). During the grain-filling period, panicle weight under elevated [CO_2] is consistently heavier than that under ambient [CO_2]. Therefore, the plant's mass moment around the base, which represents the force applied to the stem and thus the likelihood of lodging, may increase if the culm length does not decrease to compensate under elevated [CO_2]. However, no information is available on the effects of elevated [CO_2] on the relationship between culm length and panicle weight. In addition, the internodes immediately above the base of a shoot, which compose the culm, are an important factor in the physical strength of the culm; shorter and thicker lower internodes increase lodging resistance (Matsushima and Manaka, 1961; Matsuzaki et al., 1970), but the effect of elevated [CO_2] on internodes has also not been determined.

Internode elongation is also affected by the plant's nitrogen (N) status. Matsushima and Manaka (1961) subjected rice to excess N treatment at different growth stages and showed that applying excess N treatment just before the panicle-initiation stage greatly increased internode length. In contrast, Matsuzaki et al. (1970) showed that a N deficit treatment significantly shortened the internodes. The effects of N also may interact with the effects of [CO_2]. For example, elevated [CO_2] enhances carbon fixation and dilutes absorbed N within the plant tissue as a result of the increased tissue biomass (Kim et al., 2003). If a plant's N status is the primary factor in determining internode elongation, elevated [CO_2] may shorten the internodes and increase lodging resistance by means of this dilution effect.

To ensure that high yield will be maintained under elevated [CO_2], farmers may have to increase N fertilization compared with the levels required under current [CO_2] conditions (Ziska et al., 1996; Kimball et al., 2002; Kim et al., 2003). Growth under elevated [CO_2] will require higher N fertilization than under current [CO_2]. To provide adequate N fertilization under future levels of [CO_2], the interaction between [CO_2] and N fertilization must be understood, particularly with respect to lodging resistance. A number of studies have focused on the responses of lodging to environmental factors such as N fertilization and light (Matsushima and Manaka, 1961; Matsuzaki et al., 1970; Matsuda et al., 1984; Kamiji et al., 1993; Ookawa et al., 1993), but no studies have evaluated the effect of elevated [CO_2] on lodging. This is because lodging must be determined at the canopy scale in open-air fields rather than in growth chambers. This problem can be solved by free-air CO_2 enrichment (FACE), a technology that has been developed since 1989 for several crop and tree species (Kimball et al., 2002). This FACE approach enables plants to be grown under elevated [CO_2] with minimal artifacts. The objective of this research was to study the effects of interactions between elevated [CO_2] and N fertilization on lodging and the contribution of lodging to yield losses in rice in the field using a FACE system.

2. Materials and methods

2.1. Treatments

2.1.1. CO_2 enrichment

We grew rice cultivar 'Akitakomachi' under two levels of atmospheric [CO_2] throughout the crop season from germination to maturity for 24-h per day: ambient [CO_2] and an elevated level targeted at ambient [CO_2] + 200 μmol mol^{-1}. Germinated seeds were sown on 26 April 2004 in plug trays with three seeds per cell and seedlings were raised under ambient or elevated [CO_2]. The seedlings were transplanted into eight paddy fields at Shizukuishi, Iwate, Japan (39°38′N, 140°57′E), on 20 May at a density of 19.1 hills m^{-2}, 17.5 cm between hills, and 30 cm between rows. Four of the paddy fields were assigned to the elevated [CO_2] treatment. To avoid contamination of the ambient [CO_2] plots by CO_2 released in the FACE plots, each paddy field was separated from the next field by at least 90 m, a distance that ensured sufficient dilution to restore ambient [CO_2]. In each of FACE plots, an octagonal FACE ring 12 m in diameter was installed. A detailed description of this setup was provided by Okada et al. (2001). Briefly, [CO_2] at the center of the ring was monitored at 5-s intervals, and pure CO_2 was released from the peripheral emission tubes 0.5 m above the canopy, with the emission source chosen with respect to wind direction so as to maintain [CO_2] within the ring at 200 μmol mol^{-1} above the level in the ambient [CO_2] plot. The daytime [CO_2] averaged over the season was 548 ± 27 μmol mol^{-1} in the elevated [CO_2] plots and 365 ± 12 μmol mol^{-1} in the ambient [CO_2] plots. The whole-day [CO_2] level averaged was 576 ± 33 μmol mol^{-1}