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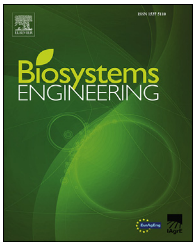

Research Paper

Dynamic distribution of thermal effects of an oscillating frost protective fan in a tea field

Kensuke Kimura [a], Daisuke Yasutake [b,1], Kentaro Nakazono [c], Masaharu Kitano [b,*]

[a] Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University, Fukuoka 812-8581, Japan
[b] Faculty of Agriculture, Kyushu University, Fukuoka 812-8581, Japan
[c] Fukuoka Agriculture and Forestry Research Centre Yame Branch, Fukuoka 834-1213, Japan

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Wind machines are one of the most effective and prevalent methods of frost protection for crops. However, their physical and physiological effectiveness should be re-examined because climate change from global warming can reduce the cold tolerance of crops, leading to higher risk of frost damage. Here, we experimentally elucidate thermal effects of a wind machine by spatiotemporal analysis of leaf heat balance, with the aid of a new method facilitating continuous and multipoint evaluation of leaf boundary layer conductance (G_A). G_A regulates convective heat exchange between leaves and ambient air. This analysis was performed in a tea field with a frost protective fan (oscillating wind machine), thereby visualising the spatiotemporal distribution of thermal effects from the oscillating fan. Those effects showed a dynamically varying distribution in space and time, as shown in the supplementary animation, under strong influences of both changes in G_A and air-to-leaf temperature difference. The change in G_A was synchronised with airflow from the oscillating fan onto leaves. However, the change in air-to-leaf temperature difference was complicated, with delay in transient thermal responses of leaves and ambient air. These spatiotemporal characteristics of thermal effects varied substantially with field location, owing to different intervals and durations of airflow from the oscillating fan. Consequently, remarkable non-uniformities in thermal effects appeared across the field, increasing potential risk of frost damage. These results indicate that the effectiveness of the fan still has room for improvement by considering the spatiotemporal characteristics of thermal effects reported herein, toward more reliable frost protection under global warming.

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[*] *Corresponding author*. Fax: +81 92 642 2923.
E-mail addresses: kensuke.kimura.352@s.kyushu-u.ac.jp (K. Kimura), yasutake@bpes.kyushu-u.ac.jp (D. Yasutake), nakazono-k4729@pref.fukuoka.lg.jp (K. Nakazono), kitano@bpes.kyushu-u.ac.jp (M. Kitano).
[1] Fax: +81 92 642 2924.

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1. Introduction

Frost can seriously damage crops in many parts of the world, for example, grape, peach, pear and citrus in the United States (Battany, 2012; Edling, Constantin, & Bourgeois, 1992; Gu et al., 2008), apple in Portugal (Ribeiro, Melo-Abreu, & Snyder, 2006), cherry in Argentina (Cittadini, de Ridder, Peri, & van Keulen, 2006) and tea in China and Japan (Lou, Ji, Sun, & Zhou, 2013; Tomihama, Nonaka, Nishi, & Arai, 2009). Climate change from global warming increases the risk of such frost damage (Augspurger, 2009, 2013), owing to the delay in cold acclimation of crops in autumn–winter (Loveys, Egerton, & Ball, 2006) and the acceleration of de-acclimation in spring (Woldendorp, Hill, Doran, & Ball, 2008). Frost damage in recent years has caused huge economic losses in crop production, e.g., 112 million USD during 2007 in North Carolina alone (Gu et al., 2008) and 268 million USD during 2010 in China (Lou et al., 2013). Woldendorp et al. (2008) noted that fatal frost events may still occur even under future global warming. Therefore, to prevent frost damage becoming more serious, conventional methods of frost protection should be improved by re-examining their physical and physiological effectiveness for plant organs (leaves, flowers and fruits).

As one of the conventional methods of frost protection, wind machines are widely used under temperature inversion conditions formed by radiative cooling with light winds and clear skies (Snyder & Melo-Abreu, 2005). These machines drive airflow horizontally or downward to increase temperatures at crop level through the following two processes: (i) warmer airflow driven by the machine at the upper layer of the temperature inversion sweeps away cooler air at the inversion bottom at crop level; (ii) airflow from the machine enhances forced convection through the boundary layer onto crop surfaces, improving heat exchange between the crops and ambient air. There has been much useful research with a focus on process (i) (e.g., Battany, 2012; Doesken and Renquist, 1989; Gerber, 1979; Ribeiro et al., 2006), but little on process (ii). The latter process, however, also considerably affects the heat balance of crops by increasing boundary layer conductance and regulating convective heat transfer over crop surfaces; i.e., sensible and latent heat fluxes are promoted via the boundary layer. Therefore, to improve frost protection methods using wind machines, their thermal effects on crops must be primarily quantified through heat balance analysis of plant organs, with consideration of both processes (i) and (ii). Moreover, to determine dynamic characteristics of the thermal effects of wind machine operation, the spatiotemporal distribution of those effects at field scale should be evaluated by continuous and multipoint analysis of the heat balance of plant organs. One of the key problems in such dynamic analysis is continuous and multipoint evaluation of boundary layer conductance for the crop surfaces. Generally, the conductance is analytically estimated from semi-empirical formulae, using wind speeds near the crop surfaces on the basis of heat transfer theory (e.g., Monteith & Unsworth, 2013). However, this estimation is not appropriate for accurate assessment of spatiotemporal changes in the boundary layer conductance during a night with frost, because of difficulty in multipoint measurement of continuous changes in the slower wind speeds near the crop surfaces. Instead of estimation using wind speed, there are methods for direct evaluation of realistic boundary layer conductance of leaves (Defraeye, Verboven, Ho, & Nicolai, 2013).

We propose herein a method for continuous and multipoint evaluation of leaf boundary layer conductance using numerous artificial leaves in crop fields, thereby facilitating spatiotemporal analysis of leaf heat balance under frost protection. This dynamic analysis of that balance was used to determine the spatiotemporal distribution of the thermal effects of an oscillating frost protective fan in a tea field during a frost night.

2. Materials and methods

2.1. *Experiment in a tea field*

The experiment was conducted within a tea field in Fukuoka, Japan (Fukuoka Agriculture and Forestry Research Centre Yame Branch; 33°13′24″N, 130°38′48″, 144 m a.m.s.l.) during a severe frost night (December 19, 2014) with strong radiative cooling caused by clear skies and light wind. The tea field had a total area of 1.5 ha, in which an experimental area of 180 m^2 (12 m × 15 m) was located in the northwest corner of a rectangular area of 816 m^2 (24 m × 34 m) (Fig. 1). In the field, tea plants (*Camellia sinensis* L. O. Kuntze) were planted in 1992 at a density of 2.5 plant m^{-2}. With canopy height 0.75 m, the plants were grown in rows oriented in a north–south direction, with row spacing 0.3 m. In the tea canopy, the most susceptible location for frost damage was the top surface, where leaves were concentrated within about a 15-cm layer, with leaf area index from 3.5 to 8.5 (Banerjee, 1992, pp. 25–51). Therefore, the heat balance of tea leaves was analysed for the top surface of the canopy.

A frost protective fan (DFC 710, Fulta Electric Machinery Co., Ltd., Nagoya, Japan) was installed in the northeast corner of the experimental area (Fig. 1). The fan head was mounted on an 8-m steel tower and had a triple-propeller blade with spin rate ~1100 rpm. The motor output power of the fan was 0.98 kW, which drove airflow of 1150 m^3 min^{-1}. The fan head was tilted 40° downward from the horizontal, and this angle produced the strongest airflow onto the canopy surface, 8.5 m from the fan. The fan head oscillated around the tower between 0° and 90° angles, with oscillation cycle 35 s. The oscillation was decelerated as the oscillation angle approached the turning angles 0° and 90°, when the oscillation persisted for a few seconds and then accelerated as the angle approached 45°, when the oscillation speed maximised.

2.2. *Leaf heat balance and thermal effect of fan operation*

The heat balance of a single leaf depends on fluxes of net radiation, sensible heat, and latent heat (Barfield, Walton, & Lacey, 1981; Leuning & Cremer, 1988). By operating the frost protective fan during a frost night, advective heat transfer from the fan can alter heat fluxes of net radiation flux R_n (W m^{-2}) under radiative cooling, sensible heat flux H (W m^{-2}) driven by convective airflow, and latent heat flux LE (W m^{-2})