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Short communication

Infrared heater arrays for warming field plots scaled up to 5-m diameter☆

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ABSTRACT

As Earth continues to warm globally, there is a need to conduct ecosystem plot warming experiments under conditions as representative of open fields in the future as possible. One promising approach is to use hexagonal arrays of infrared heaters such as described by [Kimball, B.A., Conley, M.M., Wang, S., Lin, X., Luo, C., Morgan, J., Smith, D., 2008. Infrared heater arrays for warming ecosystem field plots. Global Change Biology 14, 309–320]. However, their plots were only 3 m in diameter (7.1 m^2), which limits the stature of vegetation to shorter than about 1 m and also limits the amount of plant material that can destructively harvested. Therefore, we tested a larger hexagonal 5-m diameter array of infrared heaters, which provided a near tripling of useable area (19.6 m^2). The number of heaters was tripled from 6 to 18, and their height above the vegetative (wheat) canopy was scaled with the diameter (0.4 times diameter = 2.0 m). Distributions of down-going thermal radiation and of the resultant warming of the vegetation were quite uniform across the plot. Moreover, the same equation previously determined from 3-m diameter plots to describe the thermal radiation efficiency as a function of wind speed was still applicable. Thus, no problems were encountered in tripling the area of the infrared heater-warmed plots.

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1. Introduction

Earth continues to warm (IPCC, 2007), and the increasing temperatures are likely to affect most living organisms. Therefore, much global change research on biological systems seeks to determine the likely consequences of warming on various organisms and ecosystems. In order to avoid experimental artifacts, there is a need to conduct such research under conditions as representative as possible of future open fields, i.e., temperature free-air controlled enhancement (T-FACE) experiments.

One approach which shows promise is to deploy arrays of infrared heaters over experimental plots. We previously demonstrated that hexagonal arrays with six 1000-W ceramic heaters provided uniform warming of 3-m diameter field plots (Kimball et al., 2008). However, plots of only 3-m diameter (7.1 m^2) are quite small for ecosystem research. They are suitable only for small-stature vegetation (<1.0 m), and even then the amounts of plant material and soil available for destructive sampling are rather limited. Thus, there is a need to scale up the apparatus to larger sizes, more like those used for CO_2-FACE experiments (i.e., Kimball et al., 2002; Nowak et al., 2004).

In fall 2007 we had 18 heaters and associated equipment available that was intended for later use in a biological experiment on three 3-m diameter plots. However, for a few

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weeks we were able to deploy all the heaters over a single plot. For the 3-m diameter arrays, we found that deploying the heaters at 45° from horizontal and pointed toward the plot center and at a height of 1.2 m (0.4 times plot diameter) above the top of the crop canopy produced good uniformity of the warming (Kimball et al., 2008). Therefore, one objective was to test whether scaling the deployment height by 0.4 times 5.0 m diameter = 2.0 m in a hexagonal pattern would similarly produce good uniformity across the larger area. Another objective was to determine whether the efficiency of the array (useable downwelling thermal radiation per amount of electrical energy input) would change in any significant way. Thus, in this short technical advance communication, we report the results of tests from increasing the infrared heater array size to 5-m diameter, which is a near tripling of plot area (19.6 m^2).

2. Materials and methods

Following Kimball et al. (2008), a larger hexagonal infrared heater array was constructed. The diameter was increased from 3.0 to 5.0 m, and the height of the heaters above the wheat plant canopy was proportionally increased from 1.2 to 2.0 m (Fig. 1). Because such an increase in diameter corresponds to a near tripling of plot area (from 7.1 to 19.6 m^2 or 2.8 times), the number of heaters was also tripled from 6 to 18. The heaters were Model FTE-1000 (1000 W, 240 V, 245-mm long by 60-mm wide) manufactured by Mor Electric Heating Assoc., Inc. (Comstock Park, MI) mounted in Model ALEX-F reflective housings (254 mm long × 98.6 mm wide × 89.4 mm high). The heaters were suspended from a triangular cable system as shown in Figs. 1 and 2a. The heaters were grouped in six sets of three heaters with each group at the points of a hexagon. The heaters were deployed at an angle of 30° from the suspension cable so as to point toward the plot center and each was tilted at an angle of 45° from horizontal toward the plot center. As before (Kimball et al., 2008), a similar array of dummy heaters consisting only of the ALEX-F reflector housings with no heating elements was also deployed over a 5-m diameter reference plot, a tactic we employed to assure that shading and other factors were as identical as possible between the heated and reference plots. When the arrays were first erected near the beginning of October 2007 and the wheat plants were in the seedling stage, the heaters were 2.0 m above the soil surface (Fig. 1). The heaters were raised on a weekly schedule, so that a month later when the wheat was about 0.15-m tall and canopy was nearly closed (Fig. 2a), and when most of the measurements were obtained, the heaters were at a height of about 2.15 m above the soil, maintaining the 2.0 m above the canopy.

Fig. 1 – Photograph of an array of 18 Mor FTE infrared heaters deployed over a 5-m diameter plot of wheat seedlings at Maricopa, Arizona on 5 October 2007. In the background are electrical panels that modulate power to the heaters, and further back is a second array of dummy heaters over a reference plot. The device on an arm from the nearest post is an infrared thermometer in a housing of PVC pipe.

Canopy temperatures in both plots were sensed using infrared thermometers (IRTs; Model IRR-PN, Apogee Instruments, Logan, Utah, USA), with individual calibrations. The IRTs were deployed close to the south edge of the plots on arms extending from the south posts (Figs. 1 and 2a) at a height of 1.67 m with the sensors pointed toward the north at an angle of 45° from horizontal. Signals from the IRT over the heated plot were corrected for radiation from the heaters and reflected from the vegetation in the 8–14 μm band for Apogee Model IRR-P IRTs (Kimball et al., 2008). The heaters were controlled using the PID control system with a similar datalogger (Model CR7, Campbell Scientific, Logan, Utah, USA), as devised by Kimball (2005). The usual set-point difference between heated and corresponding reference plots was 1.5 °C during daytime and 3.0 °C at night, although for most of the testing of radiation uniformity and for the determining of thermal radiation efficiency, the heaters were forced to be fully on. Ten-minute and hourly averages of canopy temperatures and heater output signals were recorded.

Ancillary weather data consisting of solar radiation (pyranometer, Model 8–48 Eppley Laboratory, Newport, RI), wet and dry bulb temperatures at 2-m (psychrometer, Peresta et al., 1991), and wind speed at 2 m above the soil (photochopper cup anemometer, Model 12102, R.M. Young Co., Traverse City, MI) were measured in the field a few meters away from the arrays.

The uniformity of the warming treatment was determined two ways. First, using a crane to suspend a personnel basket over the heater array, a thermal imager (Model SC2000 ThermaCAM, Flir Systems, Danderyd, Sweden) was used to obtain a thermal image of the warming pattern beneath the array with the heaters maintained at full power (Fig. 2b). Second, downwelling radiation was measured using an upward pointing pyrgeometer (Model CG3, which is the upward pointing long-wave sensor on a Model CNR1 net radiometer, Kipp & Zonen, Delft, The Netherlands). The net radiometer was mounted on a trolley which rolled on 6-m long steel tracks at a height of 2.0 m below the plane of the heaters. The tracks were deployed in the plot from just past the center to about 3.0 m outside the circular plot. The pyrgeometer was pulled along the track taking 1-m average measurements with 1 min in-between for the trolley to move and the instrument to settle on a new value. The heaters were at set at full power for the duration of the test. After the whole length of the track transect was traversed, the track was moved 1.0 m perpendicular to the transect, and the trolley was again pulled along the track taking measurements in a grid pattern.

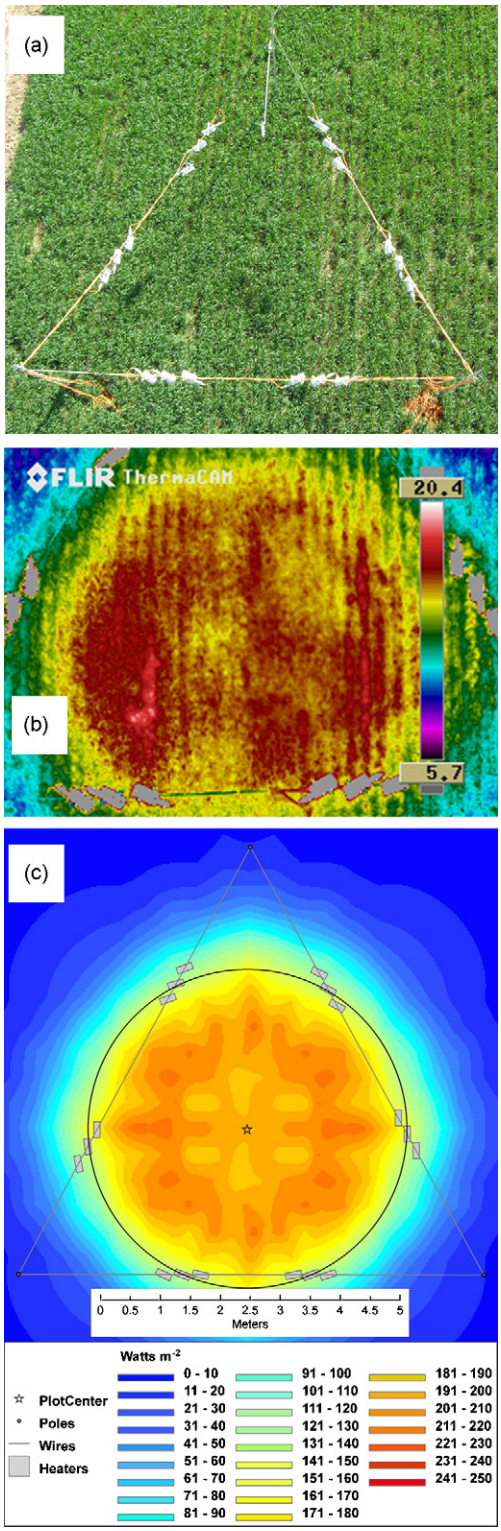

Fig. 2 – (a) Nadir view of 5-m diameter plot of wheat being warmed by 18 heaters at 2.0 m above the crop canopy and tilted at 45° toward the center in a hexagonal pattern on 6 November 2007. The heaters are suspended from cables fastened to posts in a triangular pattern outside the plot. The white rectangle at the end of a rod extending into the plot from the top of the photo is the housing of an infrared thermometer. (b) Thermal image of the warming pattern produced by the heaters in (a) obtained just before dawn on 7 November 2007 with the heaters fully on. The heaters are the rectangular grey blobs. The color-code bar on the right ranges from 5.7 °C (black) to 20.4 °C (white). (c) Measured distribution of downwelling thermal radiation at a plane 2.0 m below the heaters in (a), after adjustment for changes in sky radiation and wind speed during the 5-h measurement period and raster interpolated using ArcGIS 9.2.

About 5 h were required to complete the measurements over one quadrant of the plot area, so the values from this quadrant were symmetrically copied for the other quadrants to compete the pattern for the whole circular plot (Fig. 2c). Heater output was corrected for the 4.5–42 μm transmittance window of the instrument by dividing the values by 0.574 (Kimball, 2005). In order to account for the changing sky and temperature conditions over such a long measurement period, simultaneous measurements of downwelling sky thermal radiation several meters outside the plot were made with another pyrgeometer (Model PIR, Eppley Laboratories, Newport, Rhode Island). Changes in the downwelling sky radiation detected by this "outside" pyrgeometer were applied to the readings from the trolly-mounted pyrgeometer so as to isolate the downwelling radiation from the heaters. Similarly, there were variations in wind speed during the course of the measurement period (average = 1.23 m s^{-1}, range = 0.2–5.9 m s^{-1}), which affected the efficiency of the heater and therefore caused changes in the amount of downwelling thermal radiation. To compensate for the wind effects, the efficiencies at the mean wind speed and at the wind speed observed at each measurement time were computed from $\varepsilon = 10 + 25e^{(-0.17u)}$, where ε is the efficiency (%; amount of downwelling thermal radiation per amount of electrical energy input; see Fig. 3 and associated discussion), and u is wind speed (m s^{-1}) at 2 m. Then the downwelling radiation values were adjusted using $R_{adj} = R_x[1 + (\varepsilon_m - \varepsilon_x)\varepsilon_m{}^{-1}]$, where R_{adj} is an adjusted value (W m^{-2}), R_x is an observed value already corrected for sky radiation changes (W m^{-2}), ε_m is the efficiency calculated for the mean wind speed, and ε_x is an efficiency calculated for the wind speed at the time of the R_x observation. The resultant data were entered into a geographic information system program (ArcGIS 9.2) for visualization and interpretation (Fig. 2c).

To determine the thermal radiation efficiency (percentage of electrical power input that is emitted as down-going thermal radiation over the field plot) of the 5-m diameter infrared heater array, measurements of down-coming thermal radiation at the top of the wheat canopy near the center of the array were made using the aforementioned Eppley pyrgeometer corrected for the 3.5–50 μm transmittance window of the instrument by dividing the values by 0.60. Simultaneous measurements of down-coming thermal radiation just outside the plot were made with the up-looking thermal radiation sensor of the aforementioned Kipp and Zonen net radiometer. The array was operated at full power from 23 to 26 November 2007, during which time a wide range of wind speeds occurred. Because the heaters were continuously fully on, the electrical power input was easily determined from voltage and current measurements.

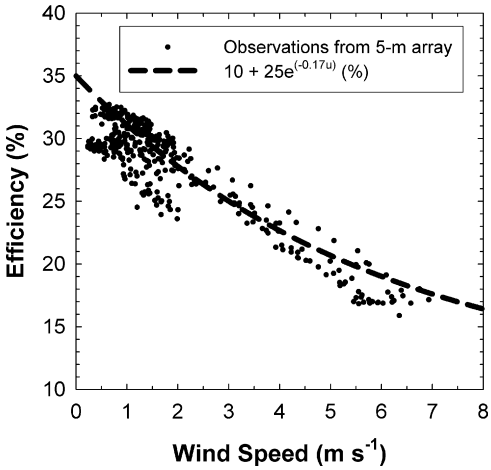

Fig. 3 – Ten-minute average thermal radiation efficiencies versus 10-min average wind speed at 2-m height measured for 5-m diameter hexagonal array of 18 Mor FTE infrared heaters over wheat at Maricopa, AZ, November 2007. The dashed curve is the equation determined previously by Kimball et al. (2008) for 3-m diameter arrays with 6 Mor FTE heaters.

3. Results and discussion

The short-term performance of the control system for the 5-m diameter array was very similar to that of 3-m diameter arrays, as expected [data not shown. See Fig. 7d of Kimball et al. (2008) for example]. However, the time available for operational testing was too short to obtain longer term seasonal averages of deviations from the set-point differences such as reported by Kimball et al. (2008, Fig. 8). Nevertheless, we found no reason to suspect any longer-term changes in control performance.

A thermal image was obtained just before dawn on 7 November 2007 when the wheat was approaching full canopy cover, although there were a few gaps in the canopy where soil was visible from above (Fig. 2a). Comparing the blue corners of Fig. 2b, which were outside of the plot, with the yellow-to-red canopy areas with no gaps within the plot, under the calm dawn conditions with full power, the system raised the canopy temperature about 7 °C. Over most of the plot area itself where there were no gaps, the color range from yellow to red shows a canopy temperature range of less than 2 °C, which we judge to be a quite uniform distribution of the warming (Fig. 2b).

Such uniform warming of the vegetation (Fig. 2b) is a consequence of the similar uniform pattern of downwelling thermal radiation from the infrared heaters (Fig. 2c). After adjusting for changes in wind speed and downwelling sky radiation, the average increase in downwelling thermal radiation from the heaters during the measurement period across 1936 pixel points within the 3-m diameter circular plot in Fig. 2c was 185 W m^{-2} with a standard deviation of 20 W m^{-2}. Therefore, a hexagonal array deployment of heaters like that used for 3-m diameter plots (Kimball et al., 2008) can be used for 5-m diameter plots, with the height of the heaters above the vegetation canopy being 0.4 times the plot diameter.

The thermal radiation efficiency (downwelling useable thermal radiation from the array per amount of electrical energy input) decreased from about 31% to about 18% as 10-min average wind speeds increased from 1 to 7 m s^{-1} (Fig. 3). At low wind speeds (<2 m s^{-1}) there appears to be a tendency for less change with wind speed, which corresponds to the condition when natural convection theoretically would predominate over forced convection (Kimball et al., 2008, Fig. 4). Nevertheless, at any given wind speed, the efficiency of the 5-m array (Fig. 3) was very close to that observed previously with a 3-m diameter array (Kimball et al., 2008, Fig. 4). In fact, the curve in Fig. 3 [efficiency (%) = 10 + 25e$^{(-0.17u)}$ where u = wind speed at 2-m height (m s^{-1})] is not fitted to the data in Fig. 3, but rather it is the curve fitted previously to the efficiency data for a 3-m array (Kimball et al., 2008). Obviously, the data from the 5-m array agree with the curve very well (r^2 = 0.98; mean square error = 2.0%), so the same efficiency equation can be used to predict the performance of both 3- and 5-m diameter hexagonal arrays of Mor FTE infrared heaters.

4. Conclusions

No problems were encountered when tripling the area of an infrared heater-warmed plot when the number of heaters was similarly tripled and their height above the vegetation canopy was scaled with the diameter (0.4 times diameter). The distributions of downwelling thermal radiation and the resultant warming of vegetation were quite uniform across the plot. Moreover, the same equation previously determined from 3-m diameter plots to describe the thermal radiation efficiency as a function of wind speed was applicable for the 5-m diameter array.

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