Global Change Biology (2008) **14,** 309–320, doi: 10.1111/j.1365-2486.2007.01486.x

Infrared heater arrays for warming ecosystem field plots

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Abstract

There is a need for methodology to warm open-field plots in order to study the likely effects of global warming on ecosystems in the future. Herein, we describe the development of arrays of more powerful and efficient infrared heaters with ceramic heating elements. By tilting the heaters at 45° from horizontal and combining six of them in a hexagonal array, good uniformity of warming was achieved across 3-m-diameter plots. Moreover, there do not appear to be obstacles (other than financial) to scaling to larger plots. The efficiency [η_h (%); thermal radiation out per electrical energy in] of these heaters was higher than that of the heaters used in most previous infrared heater experiments and can be described by: $\eta_h = 10 + 25\exp(-0.17\,u)$, where u is wind speed at 2 m height ($m\,s^{-1}$). Graphs are presented to estimate operating costs from degrees of warming, two types of plant canopy, and site windiness. Four such arrays were deployed over plots of grass at Haibei, Qinghai, China and another at Cheyenne, Wyoming, USA, along with corresponding reference plots with dummy heaters. Proportional integral derivative systems with infrared thermometers to sense canopy temperatures of the heated and reference plots were used to control the heater outputs. Over month-long periods at both sites, about 75% of canopy temperature observations were within 0.5 °C of the set-point temperature differences between heated and reference plots. Electrical power consumption per 3-m-diameter plot averaged 58 and 80 kW h day^{-1} for Haibei and Cheyenne, respectively. However, the desired temperature differences were set lower at Haibei (1.2 °C daytime, 1.7 °C night) than Cheyenne (1.5 °C daytime, 3.0 °C night), and Cheyenne is a windier site. Thus, we conclude that these hexagonal arrays of ceramic infrared heaters can be a successful temperature free-air-controlled enhancement (T-FACE) system for warming ecosystem field plots.

Keywords: canopy temperature, climate change, ecosystems, GIS, global change, global warming, infrared heater, rangeland, thermal radiation, wind speed

Received 1 May 2007; revised version received 9 August 2007 and accepted 16 July 2007

Introduction

Atmospheric CO_2 concentrations are increasing, and earth is warming globally (IPCC, 2001). Many experiments have employed various types of controlled-environment chambers to study the effects of elevated CO_2 and/or temperature on plant carbon exchange and growth, but conditions are so unnatural that quantitative extrapolation to the field condition is questionable. Lack of confidence in the chamber approach stimulated the development of free-air CO_2 enrichment technology to study the effects of elevated CO_2 (e.g. Hendrey, 1993; Long *et al*., 2006), but analogous technology to elevate temperature under field conditions remains problematic. Several attempts have been made to heat ecosystem vegetation and/or soil without heating the air (e.g. Shaver *et al*., 2000; Shen & Harte, 2000). Soil warming cables or tubes have been used (e.g. Hillier *et al*., 1994; Ineson *et al*., 1998), which permit studying the effects of temperature on soil processes, but plant canopy temperatures are largely uncoupled from soil temperatures

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except for very short vegetation. A canopy warming treatment that could be used was reported by Pinter *et al*. (2000), who detected that the blowers used in their free-air-controlled enhancement (FACE) experiments increased canopy temperatures compared with blower-less control plots at night due to mixing of cooler canopy air with warmer air aloft. A similar canopy temperature treatment was achieved by researchers on the VULCAN Project (Beier *et al*., 2004, and others in the special Volume 7, Number 6, September 2004 issue of *Ecosytems*), who deployed covers over their plots at night to reduce infrared radiant loses. However, both of these latter treatments are operable only at night, providing limited control over the temperature regime achieved.

The approach which appears to have the fewest drawbacks is warming the vegetation with infrared heaters deployed above the canopy (Harte & Shaw, 1995; Harte *et al*., 1995; Nijs *et al*., 1996; Bridgham *et al*., 1999; Luo *et al*., 2001; Shaw *et al*., 2002; Wan *et al*., 2002; Noormets *et al*., 2004; Kimball, 2005; Hovenden *et al*., 2006). This warming effect is similar to the normal solar heating of leaves, and it is relatively energetically efficient because the leaves are warmed directly without having to overcome a boundary layer resistance, as would be required if the air were heated first.

As reviewed by Kimball (2005), Harte and colleagues (Harte & Shaw, 1995; Harte *et al*., 1995) apparently were the first to utilize infrared heaters, and their experiment on montane vegetation is continuing. They and several subsequent researchers used the heaters in a constant power mode, which resulted in large heating of the vegetation under calm night-time conditions but little warming under unstable daytime conditions (Kimball, 2005). In contrast, Nijs *et al*. (1996) and Kimball (2005) devised controllers to modulate the heat output in order to maintain a constant canopy temperature rise compared with unheated reference plots, a strategy which enables more controlled warming under both daytime and night conditions.

Kimball (2005) determined the thermal radiation efficiency (percentage of electrical power that is emitted as thermal radiation) of an infrared heater with an incoloy-sheathed heating element that has been used by the majority of infrared heating experiments. Its efficiency was low, about 20%, under outdoor field conditions. The theory of operation for infrared heaters presented by Kimball (2005) also indicated that an increase in the emissivity of the heating element should lead to increase in thermal radiation efficiency. Moreover, more recent warming experiments (e.g. Shaw *et al*., 2002; Hovenden *et al*., 2006) have utilized heaters with ceramic heating elements whose manufacturer claimed a high-emissivity of 0.96. However, the power ratings of the heaters used in these more recent experiments were rather low (250 W). Therefore, we investigated other more powerful infrared heaters (1000 W) with high emissivity ceramic heating elements. Herein, we describe how we were able to overcome poor radiation distribution uniformity of these more powerful heaters by deploying six of them in hexagonal arrays. Furthermore, we demonstrate the successful performance of these temperature free-air controlled enhancement (T-FACE) systems deployed over grazing land at Haibei, Qinghai, China, and at Cheyenne, WY, USA.

Infrared heater description

Physical description

The theoretical analysis of Kimball (2005) showed that more powerful heaters than used by most prior researchers are needed in order to produce significant warming during unstable daytime conditions. After a search of available models of ceramic heaters, it appeared that a Model FTE-1000 (1000 W, 240 V, 245 mm long × 60 mm wide) manufactured by Mor Electric Heating Association Inc. (Comstock Park, MI, USA) (Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the authors or the US Department of Agriculture) had the most power per overall area of heating element with reflective housing (Fig. 1). The manufacturer claimed the emissivity of this heater to be 0.96, which suggests it should be relatively efficient. Therefore, we purchased several 'Mor FTE' heaters for testing along with Model ALEX-F reflective housings (254 mm long × 98.6 mm wide × 89.4 mm high).

One immediate concern was that the manufacturer intended the heaters for indoor use only, and the ALEX-F

Fig. 1 'Mor FTE' infrared heater deployed at an angle of 45° from horizontal and of 30° with respect to the suspension cable.

housing had openings though which water could enter and short the wiring, thereby creating an electrical hazard. Therefore, in addition to careful grounding, we re-assembled the heater element and housing with sealant (Permatex Ultra Copper RTV silicone, Permatex Inc., Solon, Ohio, USA) in all the joints and especially around the ceramic bead insulation just above the reflector part of the assembly where wires enter an upper chamber. The stated rating of the sealant is 370 °C, but the heater element can reach 700 °C, although much of the housing is not this hot. Thus, we are not sure if this sealant will be adequate over the very long term, but over several months with several rainstorms (and some deliberate dousing), our heaters have proved durable with no problems.

The particular model of Mor FTE heaters that we initially purchased (FTE-1000-240-FRK-10-Y) had a type K thermocouple embedded in the heating element. By observing the change in temperature immediately after turning the heater on and off, the time constant of the heater was determined to be about 6.0 min for both warm-up and cool-down [i.e. after 6.0 min, $\exp(-1) = 0.368$ of the total temperature change of the heating element remained to happen]. However, we also found that this heater produced electrical noise that affected our datalogger, so we had to stop using the embedded thermocouple during normal operations.

Distribution of radiation

During summer of 2005, we deployed a Mor FTE heater over Sudan Grass (*Sorghum vulgare*) at Maricopa, AZ. Using a crane to suspend a personnel basket over the heater, a thermal imager (Model SC2000 ThermaCAM, Flir Systems, Danderyd, Sweden) was used to obtain a thermal image of the warming pattern beneath the heater (Fig. 2). The pattern was distinctly cone shaped with no area of uniform warming and therefore not suitable for experimental plots.

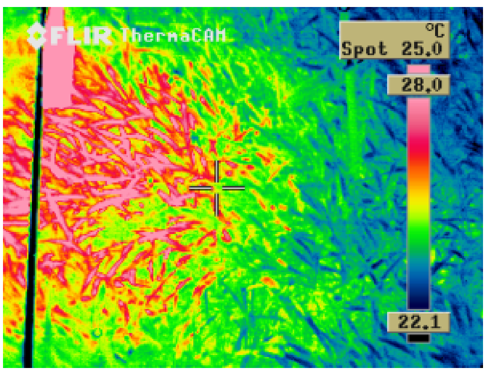

Fig. 2 Thermal image of the distribution of warming from Mor FTE infrared heater deployed at nadir over 95-cm-tall Sudan grass. The heater is the pink rectangle in the upper left of the image.

In order to distribute the thermal radiation more uniformly from the Mor FTE heaters, we expended much effort in attempts to improve the design of the reflector/housing. We were able to improve both the uniformity of the radiation distribution and efficiency as well, but the larger reflector sizes produced unsatisfactory solar shading. We then conceived of tilting the heaters at an angle and, thereby spreading the radiation over a larger area. Using a pyrgeometer (Model CG3, which is the up-looking long-wave sensor on a Model CNR1 net radiometer, Kipp & Zonen, Delft, the Netherlands) mounted on a trolley which rolled on 6-m-long steel tracks, we measured the thermal radiation distribution from a single Mor FTE heater mounted at various angles of tilt and at various heights. Heater output was corrected for the 4.5–42 μm transmittance window of the instrument by dividing the values by 0.574 (Kimball, 2005). The resultant data were entered into a geographic information system program (ArcGIS 9.1) for visualization and interpretation (Fig. 3a).

Combining heaters to form arrays with uniform radiation patterns

GIS predictions

Even when tilted at an angle of 45°, the radiation from a Mor FTE infrared heater mounted in ALEX-F reflector at a height of 120 cm above the plane of the sensor was still rather unevenly distributed (Fig. 3a), and little improvement can be seen compared with a downward facing heater (Fig. 2). However, note that some radiation, about one-sixth of that at the maximum spot, reaches a distance of 1.5 m. If a second heater were deployed on the opposite side of a 3 m plot, the ArcGIS program output shows a doubling of radiation levels at the center of the plot (Fig. 3b). Adding four more heaters to form a hexagonal pattern, the ArcGIS program predicts that the amount of radiation reaching the center would be approximately that of the maximum from a single heater, and the overall result should be a relatively uniform warming over the whole of the 3-m-diameter plot (Fig. 3c).

Hexagonal example over wheat

After seeing the encouraging interpolated ArcGIS images, we constructed a prototype array over a test crop of wheat at Maricopa, AZ (Fig. 3d). Heater outputs were measured at 111 cm below the heaters with the up-looking CG3 pyrgeometer previously described. There were some warmer spots in front of each heater and

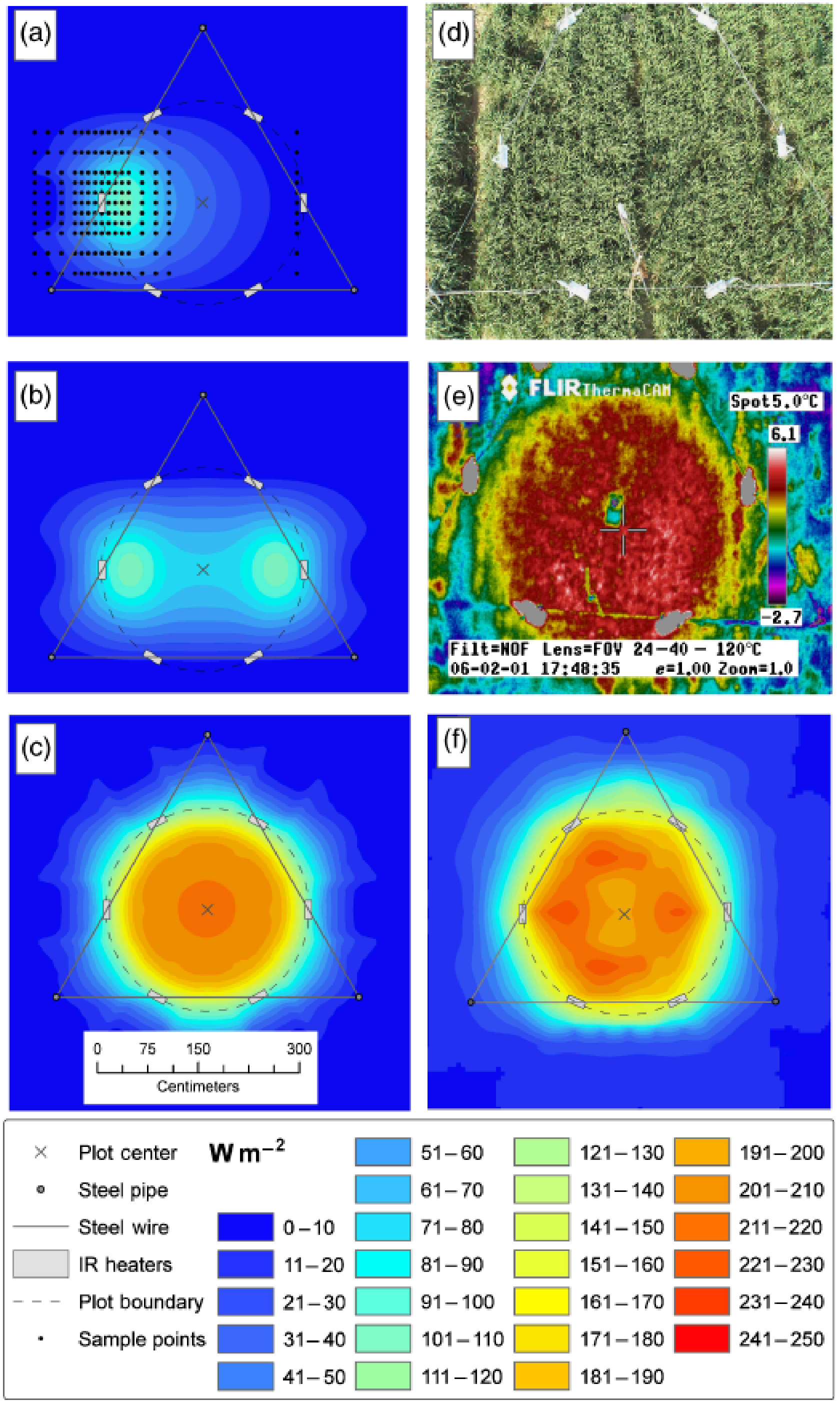

Fig. 3 (a) Measured distribution of down-going thermal radiation from a single Mor FTE infrared heater deployed at a height of 120 cm at an angle of 45° from horizontal. Black dots indicate measurement points. The color code at the bottom applies to (a–c) and (f). (b) Distribution from two such heaters facing the center from opposite sides of a 3-m-diameter plot, as predicted by an ArcGIS program. (c) Predicted distribution from six such heaters in a hexagonal pattern around the plot. (d) Nadir view of 3-m-diameter plot of 45-cm-tall wheat being warmed by six heaters at 120 cm above the crop canopy and tilted at 45° toward the center in a hexagonal pattern. 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 extended into the plot from the bottom of the photo is the housing of an infrared thermometer. (e) Thermal image of the warming pattern produced by the heaters in (d) obtained just before dawn. The heaters are the rectangular grey blobs, and the blue square near the center is an instrument. The color-code bar on the right ranges from −2.7 °C (black) to 6.1 °C (white). (f) Measured distribution of down-coming thermal radiation from the heaters in (d) determined at a plane 111 cm below the heaters.

a cooler spot in the middle, but with a range from about 150 to 200 W m^{-2} over the plot area, the distribution was adequate (Fig. 3f). Furthermore, a thermal image (Fig. 3e) showed the temperature rise of the vegetation was distributed even more uniformly across the plot than the downward thermal radiation (Fig. 3f).

The shading of the six Mor heaters (25.4 cm × 9.9 cm each) from nadir view (Fig. 3d) over a 3.0-m-diameter plot (7.1 m^2) plot would be 2%. However, considering that the heaters will be deployed around the perimeter of the circular plots, only half of the heaters will shade the plot at any one time, so the amount of shading will be closer to 1%.

We have also done some measurements with the heater mounted at higher elevations and some additional simulations using the ArcGIS program with more heaters. Except for financial considerations, we do not see any serious engineering constraints to scaling up arrays like that in Fig. 3 to larger plots with more heaters deployed at higher elevations above the vegetation. The best height appears to be about 0.8 of the radius above the canopy. The heating requirement should scale approximately with area (radius squared), but with our deployment of the heaters around the circumference, the question arises as to how many heaters can be accommodated around the perimeter and still meet the heating requirement. With room for an electrical junction box at the end, the overall length of a Mor-FTE heater is about 0.35 m. Assuming about one 1000 W heater will be required per m^2 of area (a figure that varies depending on the degrees of warming desired, on the characteristics of the vegetation, and on the windiness of the site), the maximum number of 0.35-m-long heaters that could be accommodated is 103 around a 11.4-m-diameter plot. However, it should be possible to mount the long dimension vertically rather than horizontally, which would decrease the perimeter length required per heater to about 0.12 m. For this case 873 heaters could be deployed around plots of 33.4 m diameter. But if finances allow, even larger plots could be accommodated by adding more heaters at additional heights.

Thermal radiation efficiency

To determine the thermal radiation efficiency (percentage of electrical power input that is emitted as downgoing thermal radiation over the field plot) of the prototype infrared heater array (Fig. 3d), measurements of down-coming thermal radiation at the top of the wheat canopy near the center of the array were made using a pyrgeometer (Model PIR, Eppley Laboratories, Newport, RI, USA) corrected for the 3.5–50 μm transmittance window of the instrument by dividing the values by 0.6. Simultaneous measurements of downcoming thermal radiation just outside the plot were made with the up-looking thermal radiation sensor of the aforementioned Kipp and Zonen net radiometer. Ancillary weather data were obtained from a weather mast a few meters away consisting of solar radiation (pyranometer, Model 8–48 Eppley Laboratory) wet and dry bulb temperatures at 2 m (psychrometer, Peresta *et al.*, 1991), and wind speed at 2 m (generator-type cup anemometer, Model 12102, R. M. Young Co., Traverse City, MI, USA). The hexagonal array was operated at full power from March 22 to 29, 2006, which enabled the electrical power input to be easily determined from voltage and current measurements. Then, the hexagonal array was dismantled, and a similar octagonal array was erected with eight heaters over the same plot. The octagonal array was similarly operated at full power from April 13 to 17, 2006, during which time some unusually high winds occurred.

The resultant thermal radiation efficiencies are plotted against wind speed in Fig. 4. The upper curve was calculated using the theoretical equations derived

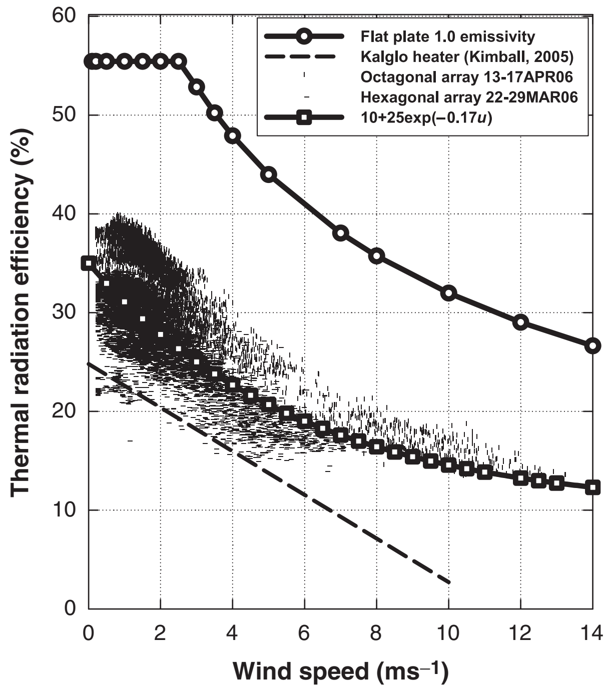

Fig. 4 One-minute-average thermal radiation efficiencies vs. wind speed at 2 m height measured for 3-m-diameter hexagonal and octagonal arrays of Mor FTE ceramic infrared heaters over wheat at Maricopa, AZ, spring 2006. The curve marked by circles is the theoretical efficiency for a flat plate of 1.0 emissivity facing downward. The curve marked by squares is an exponential decay equation fitted by eye to the data points. The dashed line is the efficiency of a Kalglo heater with a rod-shaped incoloy heating element, as determined by Kimball (2005).

by Kimball (2005) but with aerodynamic resistances for a down-facing flat plate [Campbell, 1977, Eqn (6.25)], which more closely resembles the geometry of the Mor FTE infrared heater elements than does the rod analyzed by Kimball (2005). At any given wind speed, the observed points are only about half that of the theoretical flat plate curve, probably because the heaters were tilted at an angle of 45°, rather than facing downward. Also shown is the line fitted by Kimball (2005) to a Kalglo heater with an incoloy rod-shaped heating element. (Most prior infrared heater experiments on ecosystems have used such Kalglo heaters.) At low wind speed, thermal efficiencies of the Mor FTE heaters are relatively about 40% higher (35% actual for Mor FTE compared with 25% for Kalglo). At a high wind speed of $10\,\mathrm{m\,s^{-1}}$, the relative increase was about 500%.

When data points from the hexagonal array are compared with those from the octagonal in Fig. 4, the octagonal array appears to have been slightly more efficient, although variation in the placement of the pyrgeometer within the array might be enough to account for this difference. Fortunately, however, the occurrence of unusually high winds while the octagonal array was deployed enabled the data set to encompass the vast majority of wind conditions that are likely to be encountered in the field. The curve

$$\eta_h = 10 + 25\exp(-0.17\,u),$$

was fitted by eye to the data in Fig. 4, where η_h is the thermal radiation efficiency (%) and u is wind speed ($\mathrm{m\,s^{-1}}$). This equation should be able to adequately predict operating efficiency from wind speed data for estimating electrical power requirements of ecosystem warming experiments with either hexagonal or octagonal arrays of Mor FTE heaters.

Prediction of electrical power requirements

It is possible to predict the electrical power requirements to conduct infrared heating experiments using arrays of the Mor FTE heaters from hourly weather data by using the governing equation derived by Kimball [2005, Eqn (14)] for determining the thermal radiation power needed to raise the temperature of a plot of vegetation with respect to an unheated reference plot along with the thermal radiation efficiency equation from the prior section. For example, hourly weather data from year 2004 were obtained from the USDA-ARS High Plains Grasslands Research Station near Cheyenne, WY, USA, including wind speed at 2 m. Then, assuming that the vegetation properties are those of 12-cm-tall grass (Allen *et al.*, 2005) with no dormancy (i.e. maximum evapotranspiration – a worst case scenario), the electrical power requirements per $\mathrm{m^2}$ per °C of canopy temperature rise were computed for each hour of the year.

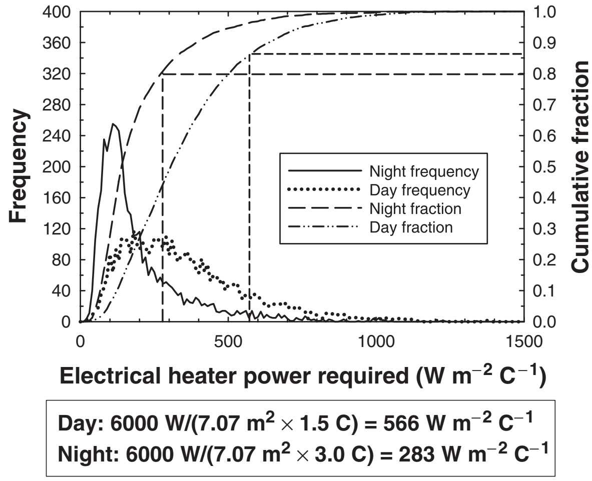

Fig. 5 Frequency and cumulative fractions of hourly electrical power requirements for infrared heating of an open-field plot using 2004 weather data from Cheyenne, WY, for separate night and daytime conditions. The vegetation properties were those of 12-cm-tall grass (Allen *et al.*, 2005) assuming no water stress or dormancy, i.e. maximum evapotranspiration. The dashed lines indicate that six Mor FTE infrared heaters (6000 W) deployed around a 3-m-diameter plot (7.07 $\mathrm{m^2}$) and warmed by 1.5 °C in daytime and 3.0 °C at night (heater system capacities of 566 and 283 $\mathrm{W\,m^{-2}\,°C^{-1}}$ for day and night, respectively) that the heating system should meet the heating requirements about 86% and 80% of the time during day and night, respectively.

The left axis of Fig. 5 shows the frequency distribution of hourly power requirements with separate curves for day (solar radiation $>5\,\mathrm{W\,m^{-2}}$) and night. Higher power requirement are required during daytime, as expected by generally higher wind speeds during daytime and especially because stomata are open during daytime and closed at night. By summing the frequency distributions, cumulative fraction curves were computed (right axis of Fig. 5). A 3-m-diameter array with six Mor FTE-1000 infrared heaters (Fig. 3) would have an electrical capacity of 6000 W, and the plot area would be 7.07 $\mathrm{m^2}$. Assuming that the amount of warming of a heated plot above that of a reference plot during the daytime would be 1.5 °C, the unit power capacity would be $566\,\mathrm{W\,m^{-2}\,°C^{-1}}$. Tracing from $566\,\mathrm{W\,m^{-2}\,°C^{-1}}$ on the x-axis upward to the day–fraction curve and then to the right, the fraction of the hours that such an array has the capacity to meet the desired heating is 0.86 (i.e. 86% of the time). Similarly, assuming that the amount of desired heating at night is twice that during the day (because night-time temperatures are rising twice as fast as daytime; IPCC, 2001), the unit power capacity would be $283\,\mathrm{W\,m^{-2}\,°C^{-1}}$. Tracing upward from 283 on the *x*-axis and then over to the right, this array would be expected to meet the night-time heating requirements 80% of the time.

If heater capacity were unlimited, so that they could meet the infrared radiation heating requirement of 1.5 °C during daytime and 3.0 °C at night no matter how windy the conditions, then summing over all hours of 2004 for the Cheyenne site revealed an annual electrical energy requirement of 34 000 kW h per 3 m array, which would cost about $3400 at an electricity price of $0.1 per kW h. However, actual arrays of six 1000 W heaters (Fig. 3) would have a maximum capacity of 6000 W, and they would fail to meet the total demand about 20% of the time (Fig. 5). Summing over all hours while limiting power supplied to 6000 W reveals an annual energy usage of 30 000 kW h (82 kW h day^{-1}) with an annual cost of about $3000 per 3 m array.

Because the cumulative fraction curves start bending more sharply toward the right at about 0.8 in Fig. 5, the returns from adding more heating capacity become more and more diminished above about 0.8. Thus, a heating system capacity that will meet the power requirements about 80% of the time represents a good compromise between performance and cost for the Cheyenne site. Analyzing weather data for several other sites, choosing a heater system capacity at about 80% of the total requirements appears to be a reasonable criteria for sizing infrared heater arrays that has some generality.

To illustrate how many 1000 W Mor-FTE heaters would be required to achieve 80% of maximum required capacity for 3-m-diameter plots, the cumulative hourly heating requirements such as shown in Fig. 5 were calculated from Eqn (14) of Kimball (2005) using 2004 hourly weather data for Cheyenne, WY, USA (a windy site; average 5.7 m s^{-1} during daytime and 4.2 m s^{-1} at night); and similarly using 2000 hourly weather data for Maricopa, AZ, USA (a site with moderate winds; average 2.2 m s^{-1} during daytime and 1.8 m s^{-1} at night). The calculations were done using the characteristics of grass (12 cm tall, minimum canopy resistances of 70 and 280 s m^{-1} for day and night, respectively), and alfalfa (50 cm tall, minimum canopy resistances of 30 and 200 s m^{-1} for day and night respectively) for whose canopies standard reference equations have been published to describe their evapotranspiration (ET, Allen *et al*., 2005). The ET reference equations do not account for dormancy or drought which would cause stomata to close, so the calculations are for maximum ET, a worst case scenario. Of course, the choice of how many degrees of warming above the reference plots directly affects the amount of heater power required, and the characteristics of the vegetative canopy and the windiness of the site do as well (Fig. 6a). To achieve 3.0 °C of warming during daytime for grass at Cheyenne, about 11 heaters would be required, compared with about five for Maricopa (Fig. 6a). The characteristics of the vegetation canopy are also very important because switching from grass to alfalfa at Maricopa raises the number of heaters required from about five to 13, even more than for grass at windy Cheyenne. At night the numbers of heaters required to achieve the same amount of warming is reduced by half or even more. However, one should probably deploy at least six heaters at a minimum in order to achieve the good uniformity of warming (Fig. 3e and f).

Similarly, to estimate the annual operating costs for electricity using the number of 1000 W Mor-FTE heaters selected to achieve 80% of the required heating demand for 3-m-diameter plots (Fig. 6a), the annual sums of power usage were calculated and multiplied by an assumed power cost of US $0.10 per kW h. As expected, power costs go up in direct proportion to the degrees of warming selected for the experiment (Fig. 6b). And as expected, the costs (Fig. 6b) are in the same relative ranking as the number of heaters required (Fig. 6a). To warm a plot using a 3.0 °C set-point difference 24 h day^{-1}, the annual operating cost would be about $4500 for grass in Cheyenne (Fig. 6b). For Maricopa, the costs for a constant 3.0 °C set-point difference would be about $2000 and $5000 for grass and alfalfa, respectively. Because night-time (i.e. minimum) temperatures are rising about twice as fast as daytime maximum temperatures (IPCC, 2001), because stomata are closed at night, and because nights tend to be less windy than days, a good case can be made to conduct warming experiments using daytime set-point differences that are one-half those used at night. The curves in Fig. 6a show that about half as many heaters are required if this control strategy is adopted. Similarly, the curves in Fig. 6b show that if the daytime set-point difference is one-half that at night, the operating costs are likely to be about two-thirds of what they would be if the set-point difference chosen for night were used 24 h day^{-1}.

Field performance over grazing land

Haibei, Qinghai, China

In May, 2006 four hexagonal arrays of Mor FTE infrared heaters like that in Fig. 3d were deployed over grass that had previously been heavily grazed by sheep during cool seasons from October to May of previous years. Four physically similar arrays with dummy heaters were deployed over reference plots.

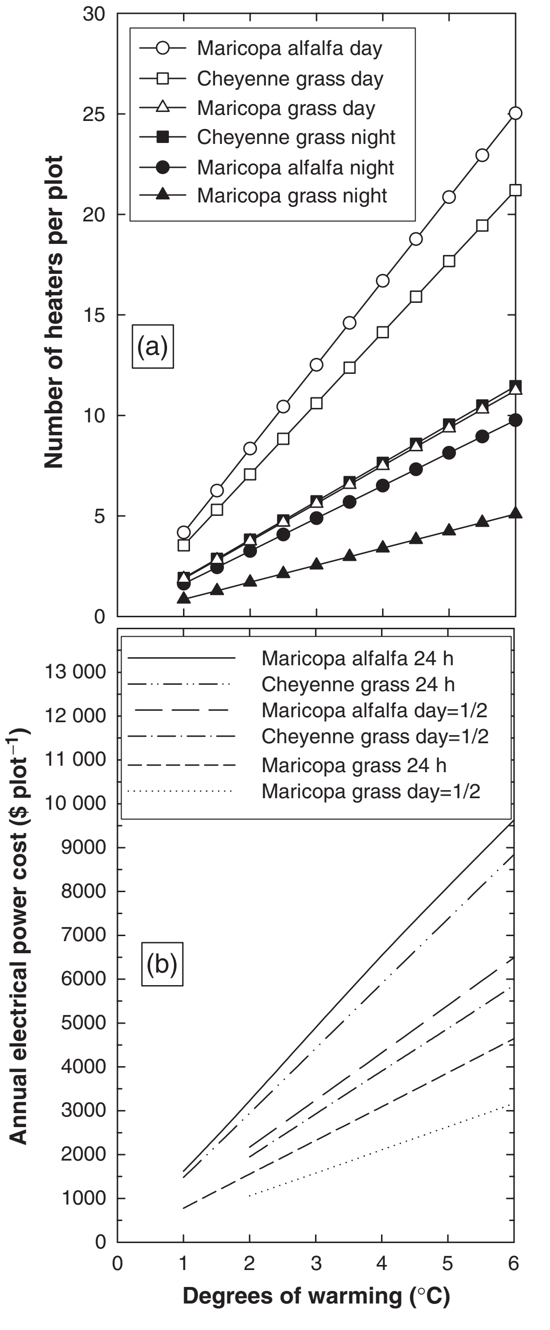

Fig. 6 (a) Number of 1000 W Mor-FTE infrared heaters required to achieve desired degrees of warming 80% of the time for 3-m-diameter plots. The curves were calculated following the procedure outlined in Fig. 5 for Cheyenne, WY, USA (a windy site) and for Maricopa, AZ, USA (a site with moderate winds); for two standard vegetation canopies (0.5-m-tall alfalfa and 0.1-m-tall grass); and for day and night separately. (b) Estimated annual operating costs to achieve desired degrees of warming per plot for heaters as given in (a) for an electricity price of $0.1 per kW h. The curves are for the given degrees of warming 24 h day^{-1} or for the given degrees of warming at night with the daytime set-point warming difference being one-half that of night-time (e.g. 1.5 °C daytime and 3.0 °C at night).

The site is at the Haibei Field Station, Qinghai, China (latitude 37°37′N, longitude 101°12′E). The station lies northeast of Tibet in a large valley (elevation of 2900–3500 m) surrounded by the Qilian Mountains (http://www.cern.ac.cn:8080/stations/second.jsp?id=446).

Canopy temperatures were sensed in each plot using an infrared thermometer (Model IRT-P5, Apogee Instruments, Logan, UT, USA), with generic calibrations. The signals from the IRTs over the heated plots were corrected for radiation from the heaters (assumed proportional to PID control signal times heater capacity times 30% efficiency) that was reflected from the vegetation (assumed 2%) in the 6.5–14 μm band for Apogee Model IRT-P5 IRTs. The heaters were controlled using the PID control system devised by Kimball (2005). The dataloggers were Model CR1000, Campbell Scientific, Logan, UT, USA with AM25T mutiplexors. The set-point difference between heated and corresponding reference plots was 1.2 °C during daytime and 1.7 °C at night. One-minute-average heater data were recorded, and ancillary hourly weather data were obtained from a nearby weather station.

There were many deviations, but generally the system was able to raise the canopy temperatures of the heated plots by the target amounts most of the time, as illustrated by a 10-day period in July (Fig. 7g and h). Soil temperatures at the 10 cm depth in the heated plots were also increased, by about 1.7 °C which is similar to the amount of the night-time canopy temperature increase. Expanding to a period over a month long and averaging over the four replicate pairs of plots, about 25% of 1-min-average observations of canopy temperature were within 0.1 °C of the desired temperature rise, about 70% were within 0.5 °C, and about 90% were within 1.0 °C (Fig. 8).

Electrical power usage per plot was calculated by multiplying the PID output signals times the total heater capacity (6000 W). Usage was affected strongly by wind speed, as expected (Fig. 7e and f). Averaging over replicates and over 625 h between July 4 and August 6, 2006, the average daily power use per 3-m-diameter plot was 58 kW h.

A comparison was made between the observed power use and that predicted from Eqn (14) of Kimball (2005). The predicted values were calculated from weather and plant properties of 12 cm grass (Allen *et al.*, 2005) with efficiency from the fitted curve in Fig. 4. The observed power use tended to be higher than predicted, especially at low wind speeds, but at higher wind speeds, the agreement was quite good. Averaging over replicates and over 625 h between 4 July and 6 August 2006, the average predicted daily power use per plot was 29 kW h, (i.e. only half that observed).

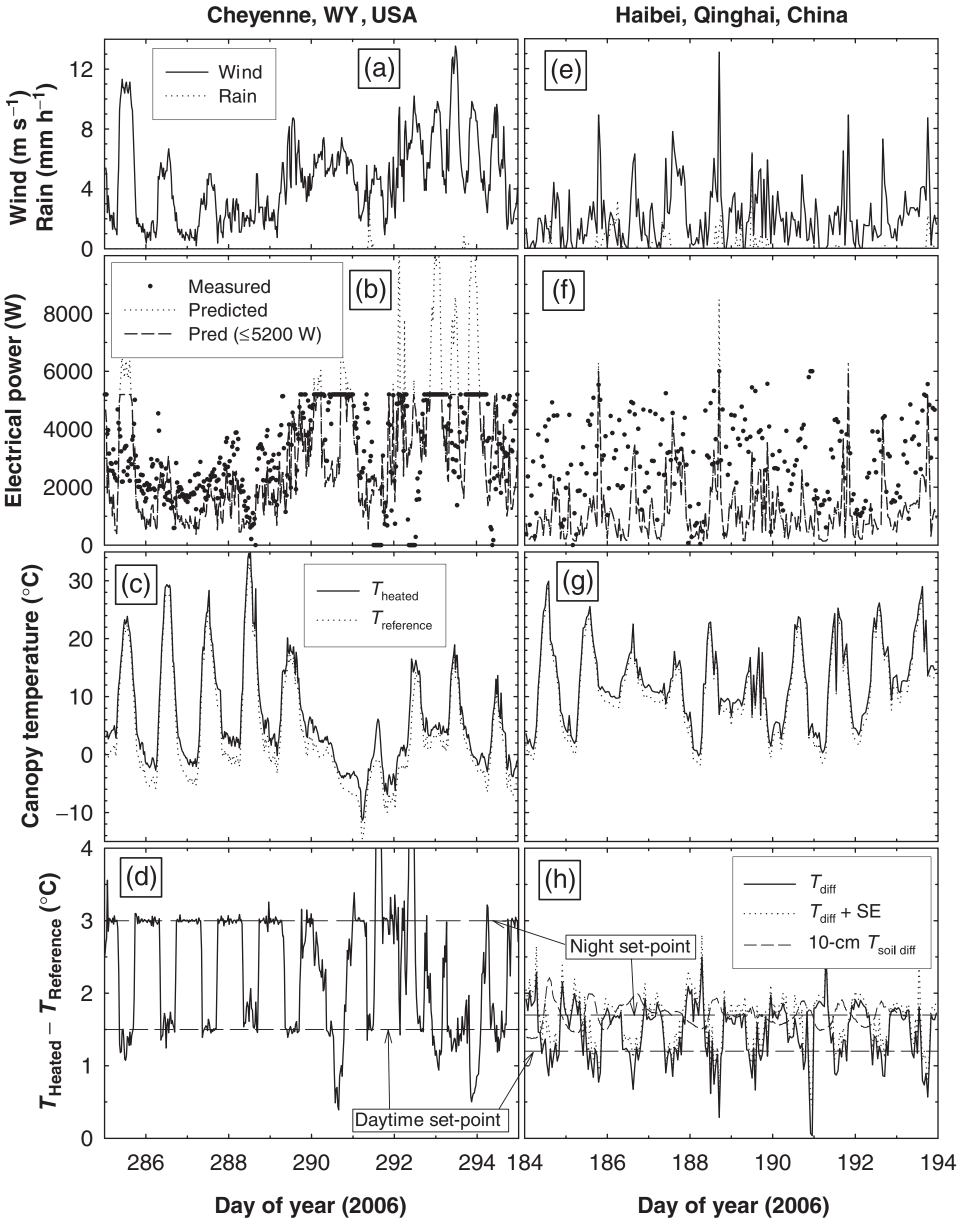

Fig. 7 Performance of hexagonal arrays of Mor FTE heaters, such as depicted in Fig. 3, that were deployed at Cheyenne, WY, USA (one array) and at Haibei, Qinghai, China (four replicate arrays) in 2006 from days of year 285–295 and 184–194, respectively. Both sites had short native grass. (a, e) Wind speeds at 2 m and rainfall (actually snowfall on DOY 191 at Cheyenne). (b, f) Measured and predicted electrical power used. The predicted requirements clipped at heater capacity (5200 W for Cheyenne and 6000 W for Haibei) are also shown. (c, g) Canopy temperatures of the heated and reference plots, as sensed by infrared thermometers. The Haibei data are the means from the four replicates. (d, h) Canopy temperature differences between the heated and reference plots, as well as the daytime and night set-point temperature differences. The Haibei temperature differences are the averages over four replicate pairs of plots. The averages plus one standard error for Haibei are also shown. In addition, the average differences in 10 cm soil temperatures between heated and reference plots are plotted.

Possible reasons for the discrepancy are (1) that the equation may be inaccurate, (2) the calibration of the infrared thermometers was inadequate, and/or (3) the measured wind speeds are too low under calm conditions when cup anemometers stall.

Cheyenne, Wyoming, USA

In July, 2006 a hexagonal array of Mor FTE infrared heaters like that in Fig. 3d was deployed over native northern mixed-grass prairie on an Ascalon soil at the

USDA-ARS High Plains Grasslands Research Station (latitude 41°11′N, longitude 104°54′W) near Cheyenne, WY, USA, along with a dummy array over a reference plot. The site has a rolling topography, with an average elevation of 1930 m. Vegetation is dominated by C_3 and C_4 grasses, with some forbs, sedges, and half-shrubs.

Canopy temperatures in both plots were sensed using infrared thermometers (Model IRR-PN, Apogee Instruments), with individual calibrations. As in China, the signals from the IRTs over the heated plots were corrected for radiation from the heaters and reflected from the vegetation in the 8–14 μm band for Apogee Model IRR-P IRTs. The heaters were similarly controlled using the PID control system devised by Kimball (2005). The datalogger was a Model CR1000, Campbell Scientific. The set-point difference between heated and corresponding reference plots was 1.5 °C during daytime and 3.0 °C at night. Half-hourly average heater and weather data were recorded.

Generally the system was able to raise the temperatures of the heated plots by the target amounts most of the time, as illustrated by a 10-day period in October (Fig. 7c and d). On day-of-year 291, snow fell (Fig. 7a) and not surprisingly, it melted first under the heated plots. Consequently, the heated plot was warmer than the reference plot for a short time without the heaters being on. This example as well as several times at Haibei illustrated how surface moisture conditions affect the canopy temperatures and decrease the ability of the system to control the temperature rise of the warmed plots. Expanding to a period over a month long, about 50% of 30-min-average observations were within 0.1 °C of the desired temperature rise, about 75% were within 0.5 °C, and about 90% were within 1.0 °C (Fig. 8).

Cheyenne is a windy site (Fig. 7a), and the set-point temperature differences were higher (Fig. 7d), so electrical power used by the heaters was usually greater than that used in Haibei (Fig. 7b compared with 7f). Averaging over 1528 half-hours between September 21 and October 24, 2006, the average daily power use per 3-m-diameter plot was 80 kW h. Referring back to the previous section and Fig. 5, the *a priori* estimate for average daily power requirement was 82 kW h day^{-1} for arrays with six 1000 W heaters. However, the power available at the Cheyenne site was 208 V, rather than the expected 240 V, so maximum capacity of an array was 5200 W, not 6000 W. Multiplying (5200/6000) times 82 = 71 kW h day^{-1}, which is in good agreement with the observed 80 kW h day^{-1}.

As with Haibei, a comparison was made between the observed power use and that predicted from Eqn (14) of Kimball (2005) from weather and plant parameters (but with the grass assumed dormant after day of year 274) (Fig. 7b). Again, the observed power use tended to be higher than predicted, especially at low wind speeds, but at higher wind speeds, the agreement is quite good. Therefore, because Cheyenne is a windier site than Haibei, overall agreement between observed and predicted was much better. Averaging 1528 half-hours between September 21 and October 24, 2006, the average predicted daily power use per plot was 68 kW h, (i.e. only 15% lower than observed).

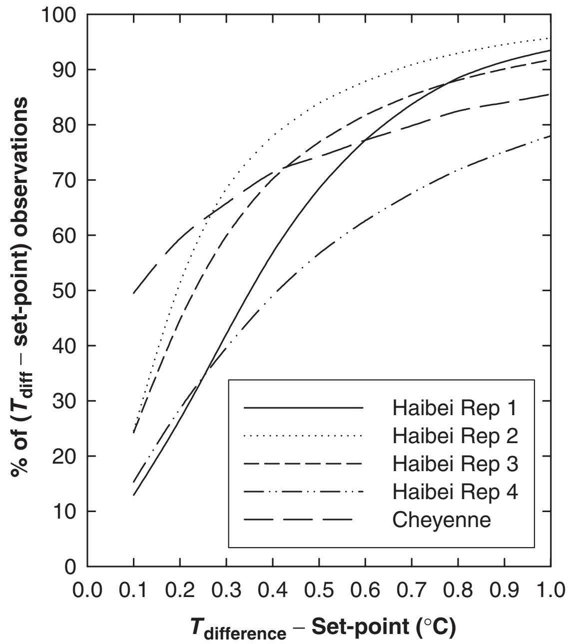

Fig. 8 Cumulative percentages of absolute values of temperature differences between heated and reference plots minus the corresponding set-point differences for the four replicate pairs of plots at Haibei, Qinghai, China and a pair of plots at Cheyenne, WY, USA. Each Haibei curve is based on 33 520 1 min average observations between July 4 and August 6, 2006. The Cheyenne curve is based on 1580 30 min average observations between September 21 and October 24, 2006.

Conclusions

1. Compared with the infrared heaters used in most previous ecosystem warming experiments, the Mor FTE ceramic infrared heaters provided more power per shaded area, and, with water proofing, they have operated for more than 11 months under field conditions with no problems.
2. By tilting the Mor FTE heaters at 45° from horizontal and combining them into hexagonal (or octagonal) arrays, good uniformity of warming was achieved over 3-m-diameter field plots, thereby creating an

improved T-FACE system. Moreover, we do not see any obstacles (other than financial) to scaling the design up to larger plots with more heaters deployed at greater heights (about 0.8 of the plot radius) above the plant canopy.

3. Efficiency [η_h (%); thermal radiation out per electrical energy in] for a 3-m-diameter plot with six heaters deployed 120 cm above the canopy can be described by: $\eta_h = 10 + 25\exp(-0.17u)$, where u is wind speed at 2 m height ($\mathrm{m\,s^{-1}}$). At moderate wind speeds ($\sim 2\,\mathrm{m\,s^{-1}}$), the efficiency was relatively about 40% greater that that of the infrared heaters with incoloy heating elements used in most prior infrared warming experiments.
4. A theoretical governing equation from Kimball (2005) can be used to estimate the electrical power cost of such arrays. The cost varies with degrees of warming, characteristics of plant canopy, and windiness of experimental site. A 50-cm-tall alfalfa canopy warmed by 3 °C at a moderately windy site (Maricopa, AZ) would cost about $5000 (at a electricity price of $0.1 kW h) per year per plot, whereas 12-cm-tall grass would cost only about $2000. At a windy site (Cheyenne, WY), warming the grass would cost about $4500.
5. Arrays deployed over grassland at sites in Haibei, Qinghai, China and Cheyenne, WY, USA achieved good control of the degree of warming above corresponding reference plots. About 75% of the observations were within 0.5 °C of the set-point temperature difference.
6. Electrical power consumption per 3-m-diameter plot averaged 58 and 80 $\mathrm{kW\,h\,day^{-1}}$ for Haibei and Cheyenne, respectively. However, the desired temperature differences were set lower at Haibei (1.2 °C daytime, 1.7 °C night) than Cheyenne (1.5 °C daytime, 3.0 °C night), and Cheyenne is a windier site.
7. Predicted power consumption from Eqn (14) of Kimball (2005) was too low at low wind speeds but agreement with measured values was good at higher windspeeds. One possible reason for this discrepancy is poor accuracy of the windspeed measurements under calm conditions.
8. Overall, the arrays of the Mor FTE ceramic infrared heaters provided reliable, controlled, relatively efficient, uniform warming of open-field plots that satisfied desired heating requirements a high percentage of the time.

Acknowledgements

The Haibei research was supported by the grants from the '100-Talent Program' and the Knowledge Innovation Program (KZCX2-XB2-06-01 and KSCX2-YW-N-040) of Chinese Academy of Science. We thank Dan LeCain and Erik Hardy for assisting in the installation of the Cheyenne equipment.

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