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Structural Design Feasibility Study for the Global Climate Experiment

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Background:

Neon, Inc. is proposing to establish a Global Change Experiment (GCE) Facility to increase our understanding of how ecological systems differ in their vulnerability to changes in climate and other relevant global change drivers, as well as provide the mechanistic basis for forecasting ecological change in the future. The experimental design was initially envisioned to consist of two complementary components; (A) a multi-factor experiment manipulating CO_2, temperature and water availability and (B) a water balance experiment. As the design analysis and cost estimates progressed, it became clear that 1) the technical difficulties of obtaining tight temperature control and maintaining elevated atmospheric carbon dioxide levels within an enclosure were greater than had been expected and 2) the envisioned study would not fit into the expected budget envelope if this was done in a partially or completely enclosed structure. After discussions between NEON management, the GCE science team, and Keith Lewin, NEON, Inc. requested Keith Lewin to expand the scope of this design study to include open-field exposure systems.

Introduction:

In order to develop the GCE design to the point where it can be presented within a proposal for funding, a feasibility study of climate manipulation structures must be conducted to determine design approaches and rough cost estimates, and to identify advantages and disadvantages of these approaches including the associated experimental artifacts. NEON, Inc requested this design study in order to develop concepts for the climate manipulation structures to support the NEON Global Climate Experiment. This study summarizes the design concepts considered for constructing and operating the GCE Facility and their associated construction, maintenance and operations costs. Comparisons and comments about experimental artifacts, construction challenges and operational uncertainties are provided to assist in selecting the final facility design. The overall goal of this report is to provide a cost and technological basis for selection of the appropriate GCE Facility design.

Design Options:

The initial experimental design envisioned using partially or completely enclosed greenhouse structures to shield multiple plots measuring at least15 m by 15 m, with a canopy height of up to 10 m. One of the major concerns of the NEON science team was the CO_2 cost of operating these facilities for 10 to 30 years. The expectation was that enclosed structures would reduce CO_2 demand by limiting air exchanges within the structure and provide the ability to exclude precipitation to induce a water stress treatment. The environmental control factors to be manipulated were [CO_2] treatments of ambient and 800 μmol mol^{-1}, temperature regimes of ambient and 4 °C above ambient, and a soil moisture availability of ambient and ~30% below ambient. All other environmental parameters including radiation, humidity, air flow were to be maintained as close to ambient as possible.

With a greenhouse, cooling the enclosed volume during the daytime is the main environmental challenge. Conventional greenhouse venting still results in inside temperatures of a few to many degrees warmer than ambient on sunny days, with shading and evaporative cooling systems often used to provide additional cooling. Using high ventilation rates to keep temperatures within the greenhouse close to ambient levels outside is in direct conflict with the goal to reduce CO_2 consumption by restricting the greenhouse air exchange rates. Reducing heat load through shading and extracting excess heat by evaporative cooling also conflict with maintaining the experimental volume at near-ambient conditions for light and humidity.

The second part of the initial experimental design, establishing multiple drought stress treatments by excluding precipitation through the use of retractable roof greenhouses is a more tractable problem. There are design considerations about whether the drought treatments will be imposed by excluding entire precipitation events or only parts of each event, but greenhouses with moveable or retracting roofs and walls are commercially available. The height of the roof above grade introduces a cost multiplier, but commercial greenhouse manufacturers consider roof heights up to 10 m to be feasible.

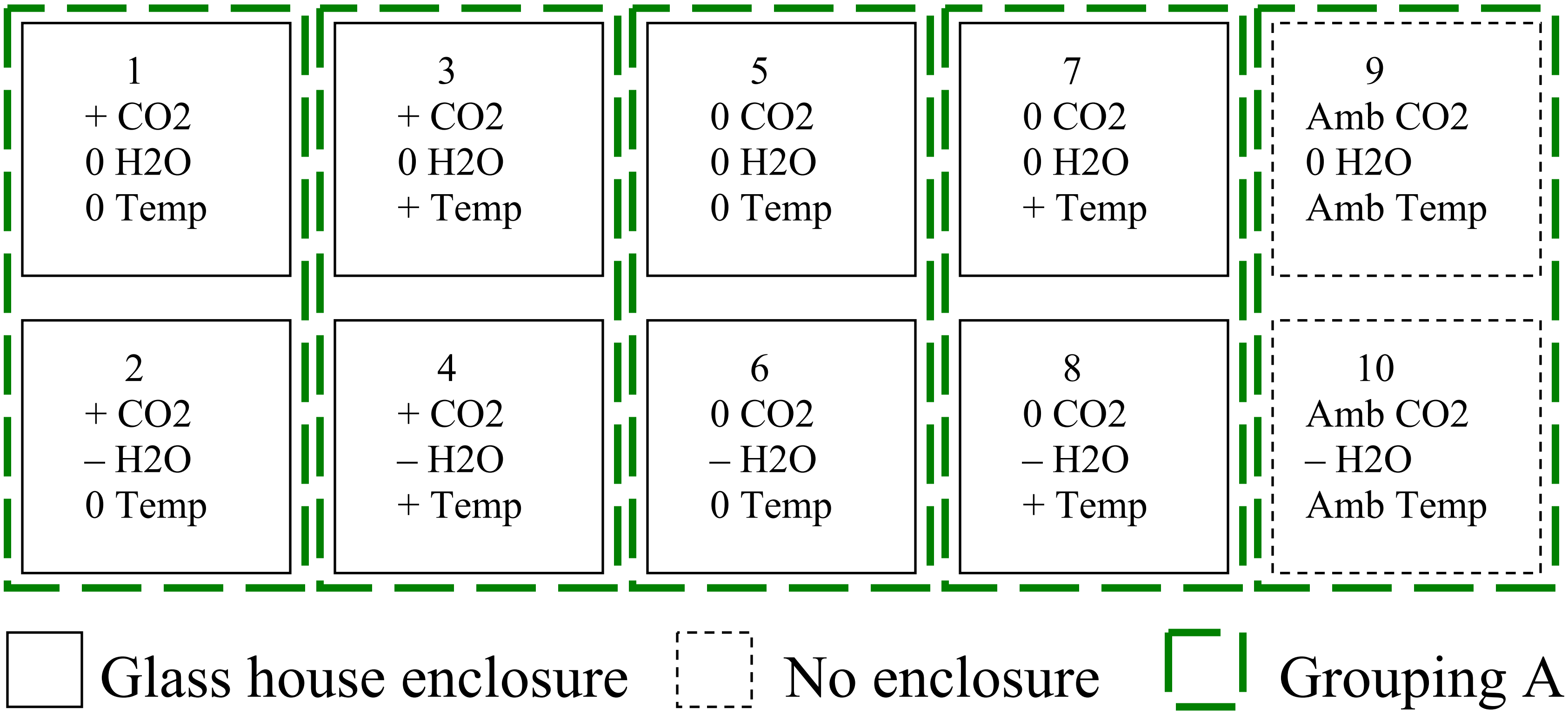
In both enclosure-based experiments outlined above, the goals were to work up a design that had high expectations of achieving the experimental goals and to determine within a reasonable degree of accuracy what it would cost to construct such a structure. The cost of construction was to include building the enclosure and purchasing and installing the mechanical components needed to achieve the desired treatments and environmental conditions. The costs were to exclude establishing research site infrastructure such as road access, electricity, water, and communications.

Since obtaining firm cost estimates would require establishing detailed structural designs and operational parameters that exceeded the scope of this activity, it was stated in the scope of work that the costs were to be determined within a "rough order of magnitude". This was done by working up basic structural designs that provided floor areas, surface areas and enclosed volumes for candidate enclosures and estimating the construction and major operational costs associated with each design. Construction costs were estimated based on conversations with Patrick Long, Institutional and Conservatory Division Manager at Rough Brothers, Inc. and Richard Vollebregt, from Cravo Equipment Ltd. (two greenhouse manufacturing companies), Kurt VandeWetering, manager of Ivy Acres, a wholesale plant growing business with 26 acres of greenhouse ranges in New York and New Jersey, and engineers at Brookhaven National Laboratory (BNL) who are currently involved in the design and procurement of new greenhouses for the BNL Biology Department.

Experimental Designs:
One of the first activities in this design and costing study was to decide on the statistical design for the CO_2 by temperature by water stress experiment. Comparisons were made for housing one treatment combination per enclosure, pairing two treatments per enclosure, and grouping combinations of treatments in a single enclosure. Placing each treatment combination in a separate enclosure would give the most flexibility in locating the treatment plots in a natural ecosystem, but would be the most expensive option to build due to the low footprint to wall and roof surface area ratio. Varying temperature or CO_2 concentration within a single enclosure requires partition walls and having to replicate CO_2 fumigation at every structure, with only one half of the structure actually needing the CO_2 fumigation hardware. Varying soil water treatments within an enclosure would require a soil barrier, roof sections that can be individually controlled, and a wider buffer area between neighboring plots, but this option is considered less expensive than the other possibilities. Placing all or most plots with a shared CO_2, temperature or water treatment in a single enclosure would be cost effective, but this design creates problems with statistical interpretation of the results. It would also be difficult to account for the spatial variability present at most locations. After considering the statistical and practical aspects of implementing the various statistical designs, the decision was made to use a complete-block, split-plot design where individual enclosures would have two water treatment plots and one of the CO_2 and temperature combinations. With this design, a replicate set of treatment plots would require four enclosures. A fifth area, with ambient CO_2 and temperature and two water treatments, but no enclosure, could be added to provide greater ability to differentiate enclosure artifacts from experimental treatment effects (Fig. 1).

The second proposed experiment involved multiple levels of water stress with ambient conditions of all other variables, including CO_2 and temperature. The design work plan called for three water balance levels. For this experiment, a complete block statistical design was chosen with the three treatments collocated under a single structure. With a preferred canopy height of 10 meters, the suggested structure was a retracting roof house with no walls. The lack of walls required greater roof overhang at the structure edges, but Richard Vollebregt, the Cravo Equipment contact, advised us that it is less expensive to increase the roof area than to add walls, especially when building a structure where the roof is 10 m above grade. With a structure this tall, much of the increased cost of adding walls would be for the bracing needed to resist wind loads on the walls, not the cost of the wall materials.

Figure 1. Treatment possibilities for 2 x 2 x 2 factorial CO_2, H_2O & temperature experiment



Enclosure Dimensions:
Once a design concept was selected, we could work out the enclosure dimensions. The initial plot size was specified as 17 m by 17 m, which was composed of a 15 m by 15 m useable plot with a 1 m border on all sides. When placing this plot size in an enclosure, additional buffer areas were needed for pathways around and between plots, clearance from enclosure walls, roof supports and vents, and clearance from roof edges to accommodate rainfall interference when precipitation events were accompanied by windy conditions.

For the multifactor experiment, the working enclosure dimensions were 40 m long by 21 m wide with a height to the roof gutters of 10 m and a height to the roof peak of 13 m (Fig. 2). A commercially available 2 bay, gutter connected greenhouse could accommodate these dimensions. The two treatment plots would be placed in the enclosure with a 2 m separation between the plots and 2 m between the plot edges and the enclosure walls. A water barrier trenched into the soil 0.5 m outside of the 17 m by 17 m plot would surround each plot. The clearances between the walls and the plots were considered minimal for this sized enclosure, especially with a 10 m canopy height.

The water balance experiment required a rain shelter with roof dimensions of 68 m by 26 m. The three 17 m square plots were arranged in a row centered in a 3 bay, gutter connected structure with retracting roof sections (Fig. 3). Each plot had a 4 m border between it and either the adjacent plot or the roof edge. Chand and Bhargava (2005) provide estimated rainfall angles of 23 degrees with wind speeds of 5 m s^{-1} and 41 degrees with 15 m s^{-1} winds. The 4 m roof overhang was selected to protect the plots from most of the wind driven raindrops when winds were less than 5 m s^{-1}. In this experiment there would also be a water barrier trenched into the soil 0.5 m outside each 17 m plot.

Figure 2. Layout of a single shelter containing two water balance plots

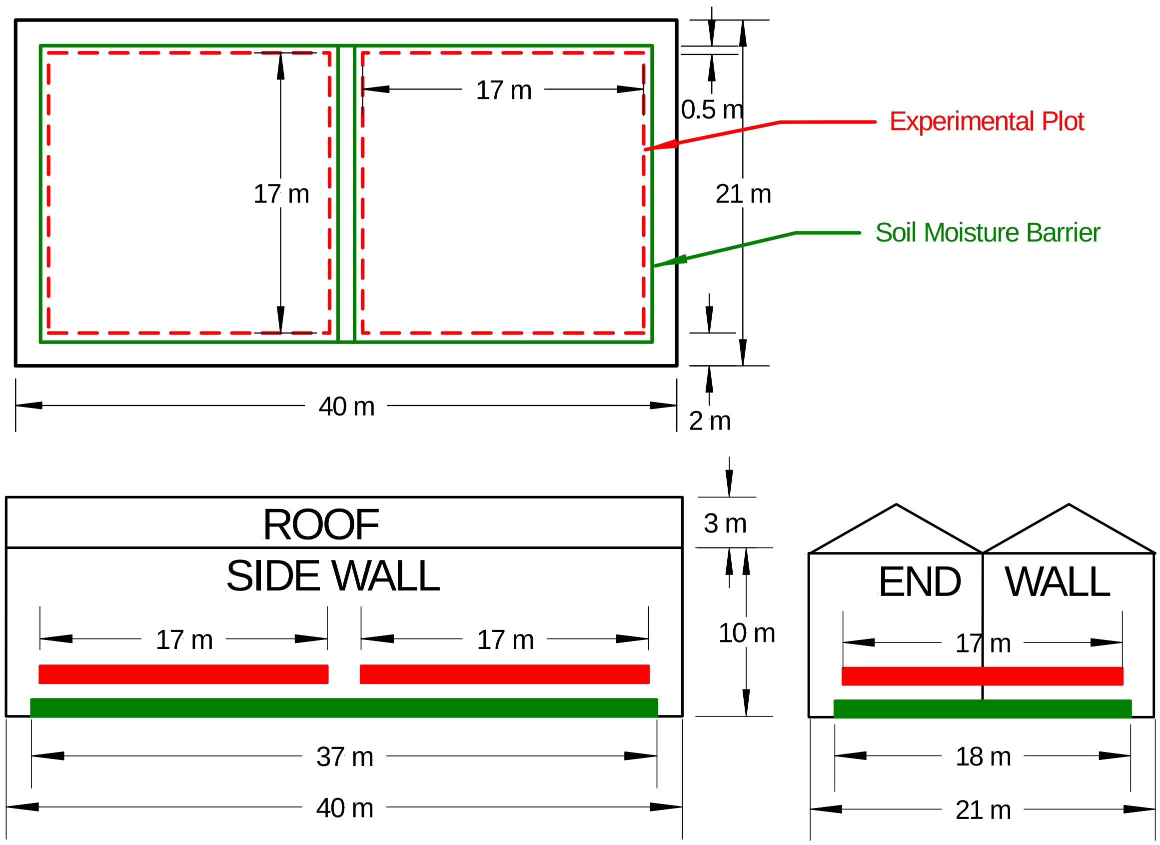
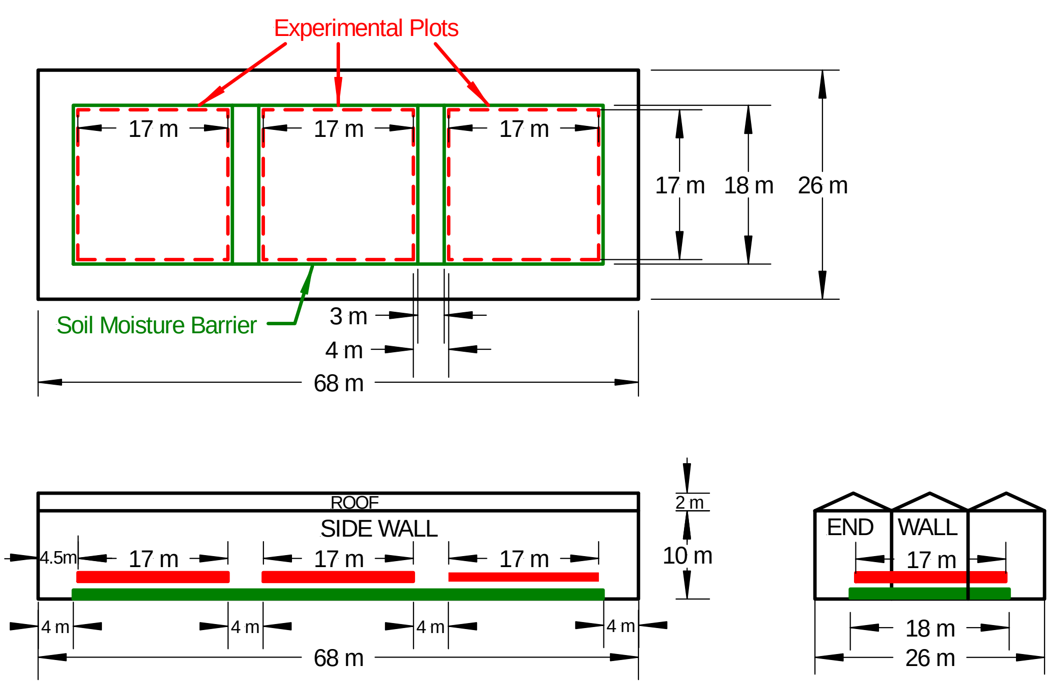


Figure 3. Layout of a precipitation exclusion shelter containing three water balance plots



Enclosure construction costs:

Greenhouse construction costs are often quoted for only the basic greenhouse structure, excluding land preparation, foundations, and installation of the electrical, mechanical and plumbing components needed to make the greenhouse functional. These costs will vary with the application, but can easily double the cost of the basic structure. When requesting cost estimates, we tried to get pricing that took into account the entire structure, including the needed CO_2 concentration, temperature and water control systems. When this was not available, we adjusted the cost to cover the additional components. We also checked pricing on a large existing greenhouse range built in the 1990's and a small research greenhouse currently being quoted at Brookhaven National Laboratory to get some bounds on construction costs.

The structure envisioned for the multi-factor experiment was a glass greenhouse with limited venting to reduce CO_2 use in the elevated CO_2 treatment. Pat Long, from Rough Brothers, Inc estimated a construction cost of \$40 to \$80 ft^{-2}, but this cost did not include site work, concrete, wire and wiring, conduit, or plumbing. This also assumed using fog or evaporative coolers and venting for temperature control. Kurt VandeWetering reported that Ivy Acres spent \$75 ft^{-2} (\$12,000,000 total) to construct a 4 acre, glass sheathed greenhouse range in the 1990's. Brookhaven National Laboratory has recently received a bid to build a glass sheathed greenhouse measuring 25 ft wide by 110 ft long by 14 ft tall to the peak. The materials cost for the basic structure is \$74 ft^{-2}. Accessories such as heaters, evaporative coolers, an automatic mist system, delivery and installation on an existing foundation increased the cost to \$97 ft^{-2}. The costs for the greenhouse foundation, electrical and plumbing are not included in the \$97 ft^{-2} price quote. Based on these benchmarks, it would appear that the total construction cost for greenhouses capable of controlling CO_2 concentration, temperature and water availability would most likely be in the range of \$80 to \$100 ft^{-2}, even if the temperature control could be accomplished with only conventional venting and evaporative cooling techniques.

The rain shelter is a much simpler structure, but not without some technical challenges. Positioning a roof 10 m above grade requires significantly more bracing than needed with a 3 or 4 m tall roof. The combination of plot size and overhang requirements makes this a sizable shelter. And while most commercial retracting roof greenhouses have large roof areas controlled by the same motor and drive system, this rain shelter will need three separately controlled roof sections to accommodate the three water treatments. In addition, if the goal is to alter the amount of precipitation allowed to land on the plot during ambient rain events, as opposed to creating the water balance treatments by excluding entire events, the retracting roof design has to be modified so it allows the same amount of water, on average, to land on all portions of each plot. A conventional retracting roof design always moves the roof from the same side, so the portion of the plot near the open position would receive less precipitation compared to the portion under the last section of the roof to close. A custom roof design should be able to alleviate this problem, but it will certainly cost more than a standard retracting roof. Richard Vollebregt of Cravo Equipment (a prominent manufacturer of retracting fabric roof greenhouses) provided estimates of \$22 to \$35 ft^{-2} for a retracting roof house with no walls and the roof positioned 10 m above grade. This cost estimate dropped to \$15 to \$18 ft^{-2} if the wall height to the gutters was reduced to 4.3 m. Neither of these cost estimates included a custom design for the roof retracting system, foundations or site preparation, so they should be considered towards the lower end of the cost scale.

Extrapolating the "per square foot" construction costs for these two greenhouse designs provides estimates for constructing individual houses, replicates, sites and the entire experiment network. The 2 x 2 x 2 split plot, complete block design requires 4 enclosures per replicate. Guidance from the NEON Science contacts, Melinda Smith and Alan Knapp, recommended using 5 replicates per site, and increasing the number of sites from two to three. With 5 replicates per site and 3 sites, we need 20 greenhouses per site, for a total of 60 houses to conduct this experiment at three locations. Each house measures 40 m by 21 m, yielding a floor area of 840 m^2. Table 1 shows construction cost estimates for the various experimental groupings.

Table 1. Construction costs for 2 x 2 x 2 split plot, complete block experiment at two price points.

Replication	Number of shelters	Enclosed area (m^2)	\$80 ft^{-2}	\$100 ft^{-2}
Shelter	1	840	$723,334	$904,168
Replicate	4	3,360	$2,893,336	$3,616,670
Site	20	16,800	$14,466,682	$18,083,352
3 Sites	60	50,400	$43,400,045	$54,250,056

The water balance experimental design differs in that an entire replicate grouping of three treatment plots fits within a single shelter. Guidance given for this experiment dictated 3 water balance treatments, five replicates per site and a total of 5 experimental sites. The construction cost estimates for the rain shelter experiment is given in Table 2.

Table 2. Construction costs for water balance experiment at two price points

Replication	Number of shelters	Enclosed area (m^2)	\$18 ft^{-2}	\$35 ft^{-2}
Shelter	1	1,768	$342,550	$666,070
Replicate	1	1,768	$342,550	$666,070
Site	5	8,840	$1,712,752	$3,330,351
5 Sites	25	44,200	$8,563,759	$16,651,753

Adjusting the number of replicates and sites can alter these numbers, but even one site exceeds the expected budget for this activity. As a comparison with another large, well known greenhouse structure, Biosphere 2 has a footprint of 1.27 ha and cost $200,000,000 to build and operate between 1985 and 2007 (http://en.wikipedia.org/wiki/Biosphere_2). One of these GCE sites with a 2 x 2 x 2 experiment and 20 greenhouses encloses 1.68 ha. A water balance site will require 0.88 ha under the rain shelter. By this comparison, the above cost estimates do not appear all that excessive.

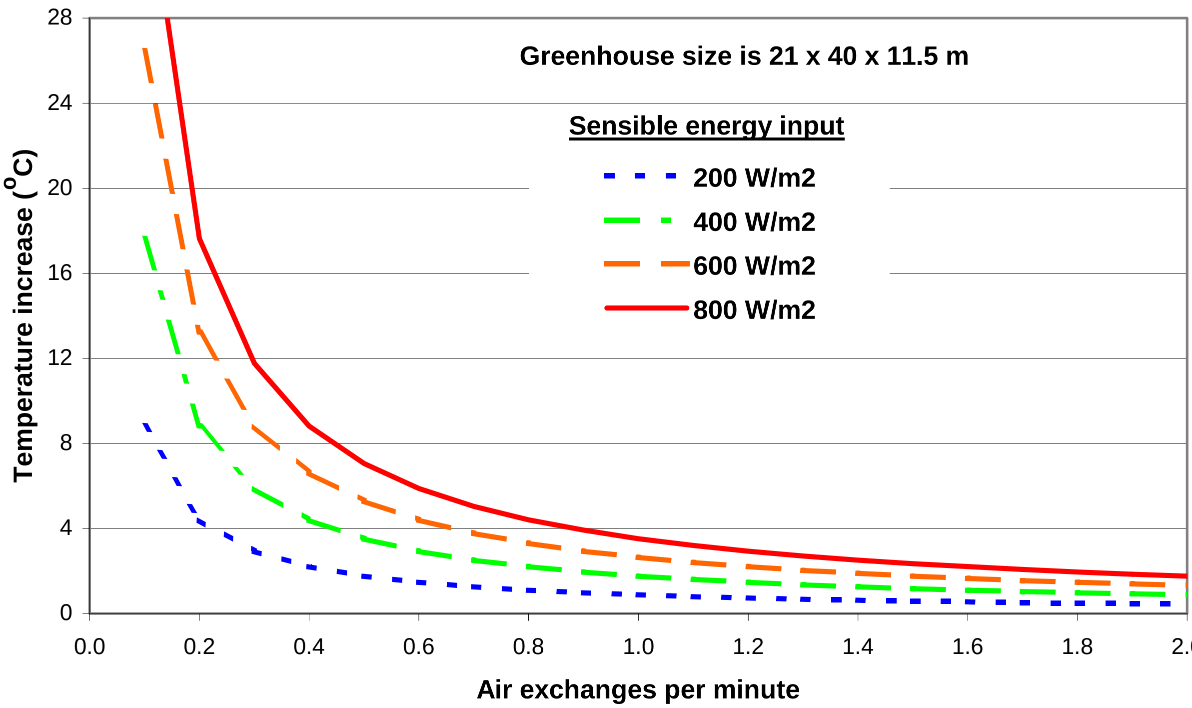
Engineering challenges:

Simultaneously controlling CO_2 concentration, temperature, and water balance within the same enclosure is a difficult task. The experimental design expects the temperature treatments to be ambient and 4 °C above ambient, both day and night. The NEON science advisors requested the temperature within the greenhouse maintained at ambient temperature be within 1 °C of the outdoor temperature. The initial driver for using an enclosure instead of an open field facility was the expectation of savings in CO_2 use and greater ease in elevating the temperature within a plot. The problem with this approach is the factors that help conserve CO_2 oppose those that assist with temperature control.

Figure 4 shows the results of a simple energy-balance box model to illustrate the effects of ventilation on greenhouse temperature elevation. Sensible energy input is global solar radiation (all wavelengths) on a horizontal surface, in this case the greenhouse footprint, minus transmission losses through the ceiling, floor and walls and minus energy that goes into water vaporization (latent heat). Maximum outdoor global radiation at a temperate site is typically about 1000 W/m^2, so 800 W/m^2 transmitted into a greenhouse is a reasonable upper limit. This model does not include heat losses due to conduction through the glazing or soil, or outgoing long-wave radiation. This simple model probably over-estimates the greenhouse temperature increase, but the modeled result agrees with the statement from Pat Long that maintaining the greenhouse temperature with a couple degrees of outdoor ambient will require 1 to 2 air exchanges per minute. It therefore provides a useful first approximation of the sensible heat load in a greenhouse under differing solar energy inputs.

Based on this model, maintaining the temperature in a greenhouse within 1 °C of outdoor ambient using only venting would require more than 1 air exchange per minute under most daylight conditions. In the elevated temperature greenhouses the temperature increase could be kept at 4 °C above ambient with air exchange rates below 1 min^{-1}. For reasons of CO_2 economy, average air exchange rates should be much smaller, on the order of 0.2 air exchanges per minute. Maintaining tight temperature control requirements will require a closed-loop system for cooling, heating and dehumidification in addition to at least some open-loop ventilation to provide reasonable flushing of the greenhouse with fresh air. To minimize environmental artifacts, air flow (intensity and pattern) and humidity should be the same in all greenhouses and within reasonable levels compared to the outdoor ambient regardless of whether the individual house is being kept at ambient or elevated temperature or CO_2 concentration. This will be difficult to achieve in any greenhouse design, but is critical when examining climate change effects on established natural ecosystems.

Figure 4. A simple energy-balance box model of greenhouse temperature increase versus air exchange rate. Sensible energy input consists of global solar radiation times a glazing transmission factor times the fraction of radiation converted to sensible heat. Energy output is the sensible heat component in air removed by open-loop ventilation. Heat losses by conduction through the greenhouse ceiling, floor and walls and by long-wave radiation are ignored.

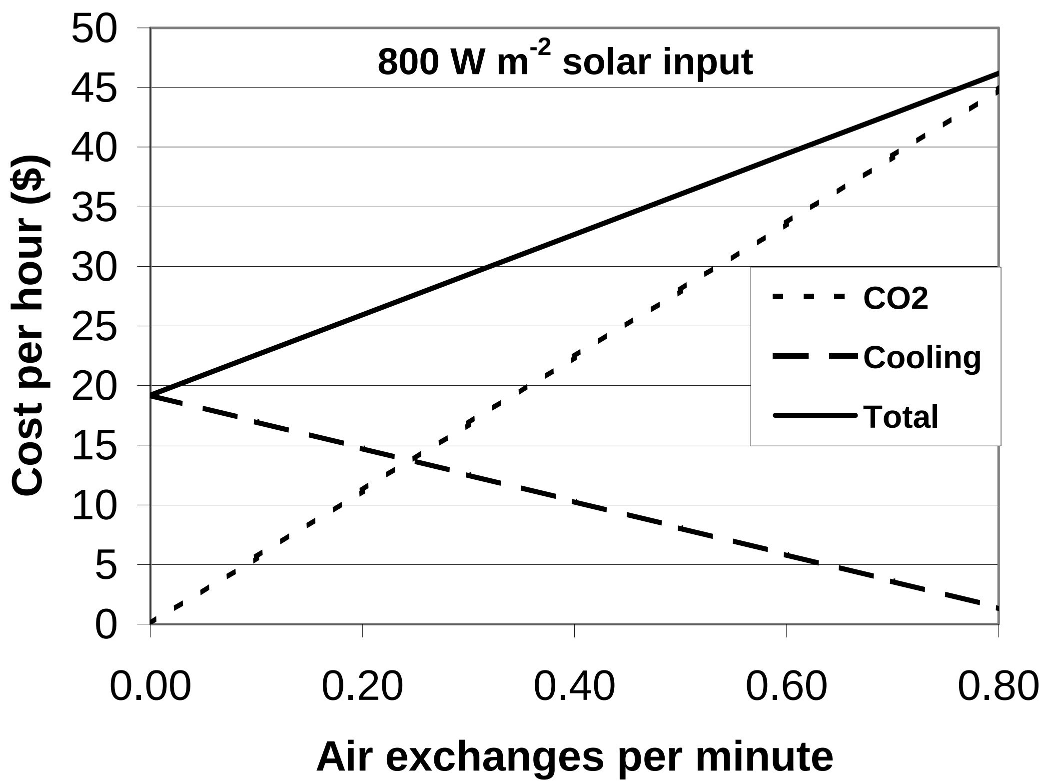


Air exchange rates above 1 min^{-1} would require large amounts of CO_2 (more than 400 kg h^{-1}) to maintain the 800 µmol mol^{-1} concentration also requested in the statement of work. Maintaining moderate CO_2 use (e.g. 100 kg h^{-1}) requires an air exchange rate on the order of 0.2 exchanges per minute, which is insufficient to maintain daytime temperatures within the desired limits using conventional greenhouse venting and evaporative cooling techniques (wet pads and pressurized fog nozzles).

The alternative to venting and evaporative cooling is to install a closed-loop mechanical air conditioning system to remove excess heat and humidity from the greenhouse. With a closed-loop cooling system we have to account for both sensible and latent heat loads, because the air conditioning system is going to have to remove moisture released into the atmosphere within the greenhouse through evapotranspiration as well as lower the temperature. We used an equation and parameters given by Davies (2005) to calculate solar heat loading of a greenhouse along with the hourly solar energy data collected at the Konza Prairie research site from 2005 to 2007 to do a test run for sizing the air conditioning demand for a greenhouse with minimal venting. Our calculations indicate we need a refrigeration system with a capacity to provide 125 tons of refrigeration for each of the 40 m by 21 m greenhouses. This would be a large, but not unobtainable, commercial refrigeration unit. Since the cooling demand varies with the solar energy, the refrigeration unit would need to have multiple stage refrigerant pumps and evaporators and a complex control system to match cooling capacity to solar heat load in real time. Based on their recent purchase of a 100 ton refrigeration unit for a conventional building, the BNL engineers estimated the cost for such an air conditioning system at over $100,000.

Figure 5 compares the estimated costs of electricity and CO_2 to determine the most cost effective balance between mechanical cooling and CO_2 use. For a 40 m long by 21 m wide by 11.5 m high greenhouse with a target treatment 400 μmol mol^{-1} above ambient, the CO_2 requirement is about 42 kg $h^{-1}$for each 0.1 air exchange per minute. At $120 per short ton for CO_2, this corresponds to an additional operating cost of $5.60 per hour per fumigation greenhouse per 0.1 air exchange per minute. This rate is essentially constant and applies whenever the plants will be fumigated. Potentially offsetting this increase cost is savings realized by partially using ventilation (assumed here to be free) to cool/dehumidify the air. For a greenhouse held to 4 °C above ambient and humidity equal to ambient, the refrigeration load will decrease by 22 tons. With a coefficient of performance of 3.5, the electrical power saved is 22 kW. At $0.10 per kWh, this is $2.20 per hour per elevated temperature greenhouse per 0.1 air exchange per minute. Savings in ambient temperature greenhouses will be much less since venting provides no net exchange of sensible heat when indoor and outdoor temperatures are equal.

Figure 5. Operating cost comparison between air conditioning energy use and CO_2 consumption. Using a simple box model, the trade off between cooling and gas expense is plotted versus air exchange rate. For 800 W/m^2 (the expected maximum radiation input considering shading and transmission losses), cooling is required up to about 0.8 air exchanges per minute. After that air heating is required so both gas and conditioning expenses go up. As the radiation input decreases, the cooling/heating crossover point decreases proportionately.



Finally, it must be acknowledged that any structure will alter the environment of the ecosystem it encloses. When attempting to study a natural ecosystem, it is difficult to maintain that ecosystem during the construction and startup phase of the experiment. Once the structures are in place and operational, any failure of the climate control system can quickly alter the ecosystem more than the experimental treatments, possibly ending the experiment.

All greenhouses cause shading. The clearest greenhouse roof spans transmit only 80% of ambient sunlight. One of the causes for the failure of plants to thrive in Biosphere 2 during the winter months was only 45 to 50% of ambient incident sunlight penetrated the structure's glazing and superstructure (Dempster, 1999). Decreased sunlight will have impacts on many environmental and plant community factors, which will affect species competition and community dynamics.

All manipulative experiments have the potential to create an "island effect" if the experimental treatment or any disturbance causes a change in a small area of the ecosystem. This discontinuity between inside and outside of the study area can change the ecosystem's functioning and balance. The walls and roof of an enclosure act as barriers for wind, rain, seeds, animals, insects and diseases, either excluding them from or retaining them within the enclosure. This discontinuity is especially strong for a natural ecosystem study, so the potential to affect the interpretation of the experimental results is high.

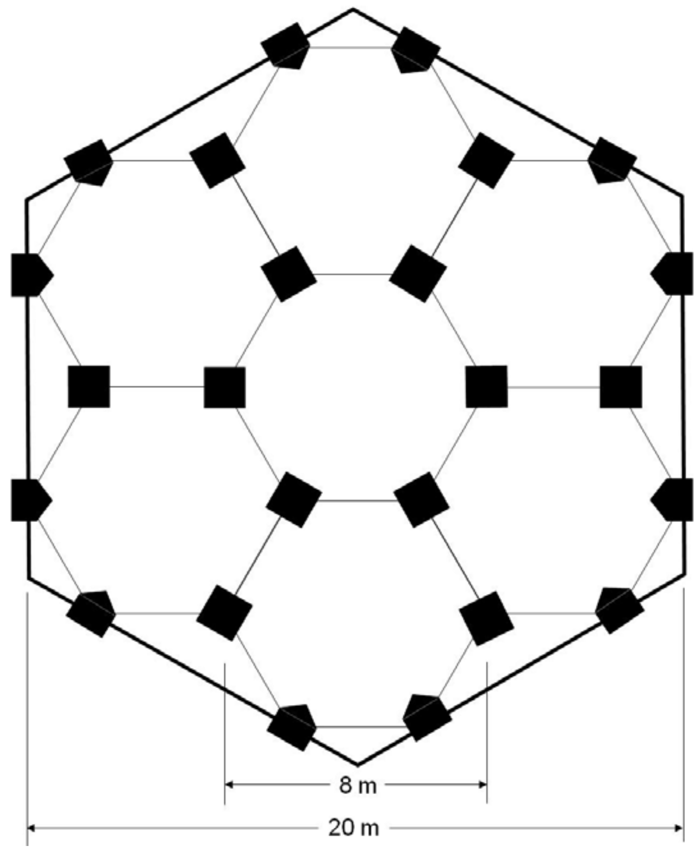
Alternative designs:
After several rounds of cost estimates and discussions of what experimental designs could both fit into the budget window and look attractive to both potential facility users and the funding agency, the decision was made to investigate open field experimental designs. Design requirements deemed critical included a target CO_2 concentration of 800 µmol mol^{-1}, canopy temperature elevation of 4 °C, maintaining useable plot areas of ~225 m^2 (15 m x 15 m) and maintaining adequate plot replication. FACE experiments have controlled the CO_2 concentrations in plot areas exceeding 500 m^2, with concentrations of 550 to 600 µmol mol^{-1}. Based on years of experience with controlling CO_2 and O_3 using FACE technology, we believe controlling the CO_2 concentration of 20 m diameter plots at 800 µmol mol^{-1} should not be a major engineering challenge. Discussions with Bruce Kimball indicated the technology of warming a low stature plants using infrared heaters could be expanded to cover 20 meter diameter plots and temperature elevations of 4 °C (Appendix 1). This would be accomplished through use of new heater designs and novel arrangements of the heaters within the 20 m plot. Adding a water balance component to the open field CO_2 and temperature experiment was investigated as well, and appears possible, but the NEON science team made the management decision to simplify the experimental design to only investigate CO_2 concentration and canopy temperature for the open air experiments. A water balance component could be added on in the future by either subdividing the existing plots or adding additional plots to accommodate the additional factor.

An open field design incorporating temperature and CO_2 elevation:
The engineering limits and energy costs of using currently available infrared heater technologies to warm a natural ecosystem are the controlling factor in the area and canopy height that can be studied using an open field experimental design. Current open field temperature elevation studies using infrared heating have used plots of 3 to 5 m diameter and commercial infrared heaters whose maximum output was 1000 W. These heaters were not designed for outdoor use or to provide uniform temperature elevation over large areas. Scaling the original experiments up to plot areas over 200 m^2 became expensive due to the number of heaters required and the cost to modify each heater unit to improve the heat distribution pattern and make the heater weather resistant. A breakthrough in this area came when Bruce Kimball located a company that made sealed infrared heaters with unit power capacities exceeding 8000 W (Appendix 3) and Keith Lewin recommended installing the infrared heaters in a honeycomb pattern of hexagons nested within a larger CO_2 FACE plot (Fig. 6). These heaters can be used outdoors as received from the manufacturer. Their power density will allow the 20 m diameter plot to be heated with ~1/10th the number of heaters required if we used the models currently used in 3 m plots, greatly reducing installation costs and plot shading issues. Distributing the heaters over the plot area instead of placing them around the periphery of the plot increases the theoretical “geometric efficiency” of transferring the heat to the area of interest to 58%, compared to 37% for a single hexagonal plot with all the heaters located around the periphery and tilted at 45° towards the plot

center. This increased efficiency reduces the number of heaters and amount of energy required to meet the 4 °C temperature elevation target.

Figure 6. Schematic diagram for the deployment of infrared heaters over a 20 m diameter hexagonal plot via the use of seven internal 8 m diameter hexagons. Three (or possibly four) heaters would be deployed at each of the 24 nodes where lines connect. The heaters at each of the 12 outer nodes would be tilted at 45° from vertical and pointed in the indicated direction, i.e. toward the center of the smaller internal hexagon, whereas the heaters at the internal nodes point nadir. The size of the square and arrow symbols at the nodes approximates the area of the heaters when viewed from nadir.

Figure and caption credit: Bruce Kimball



This open field installation reduces capital outlay for construction (Table 3) and collateral disturbance of the ecosystem under investigation during the construction and operations stages of the experiment. The estimated construction cost per square meter of usable plot area is 32% (\$633 m^{-2} versus \$2,009 m^{-2}) of the cost to provide the same usable area in a temperature and CO_2 controlled greenhouse. The energy needed to increase the canopy temperature by 4 °C in the elevated temperature plots is partially offset by the energy that would be needed to maintain the temperature in all greenhouses at ambient or 4 °C above ambient. An open field experimental design also is more protective during system failures. When the temperature and/or CO_2 control systems shut down, due to either a planned or an unplanned event, the ecosystem will go to ambient temperature and CO_2 concentration, not to extremes that might harm the ecosystem.

Table 3. Estimated construction costs for an open field 2 x 2 complete block elevated temperature and elevated CO_2 interaction experiment with 20 m diameter plots (17m usable diameter) and five replicates.

Materials cost per elevated temperature plot	$149,870
Number of elevated temperature plots per replicate	2
Materials cost per ambient temperature plot	$26,426
Number of ambient temperature plots per replicate	2
Materials cost per elevated CO_2 plot	$25,000
Number of elevated CO_2 plots per replicate	2
Materials cost for ambient CO_2 plot	$3,000
Number of ambient CO_2 plots per replicate	2
Materials cost per replicate	$408,592
Assembly labor cost per replicate	$19,200
Construction cost per replicate	$427,792
Number of replicates per site	5
Support equipment for IR plots	$3,970
Support equipment for CO_2 plots	$500
Central control center cost	$30,000
Central CO_2 storage and vaporization system cost	$500,000
Total experiment construction cost for 1 site	$2,673,430
Initial hardware engineering and programming labor	$200,000
Total cost	$2,873,430
Total plot area per treatment	1,571 m^2
Total area in all plots	6,283 m^2
Cost per square meter of total plot area	$457
Cost per square foot of total plot area	$42
Usable experimental area per treatment	1,135 m^2
Usable experimental area in all plots	4,540 m^2
Cost per square meter of usable experimental area	$633
Cost per square foot of usable experimental area	$59

The operational costs of an open field elevated temperature and CO_2 interaction study are large, but do not appear unmanageable. Current limitations on the ability of infrared heaters to penetrate and warm deep plant canopies limits this temperature elevation technique to relatively short canopies, probably less than 3 meters tall. This height limitation and the high capital and energy costs for IR heating limits the diameter and fumigation height for an open field CO_2 enrichment system to dimensions well within the capabilities of current Free Air CO_2 Enrichment (FACE) technology. A 15 m square plot has an area of 225 m^2. With a conservative estimate of a 1.5 m wide buffer around a circular Temperature/CO_2 FACE plot, a 20 m diameter plot would yield 227 m^2 of usable experimental area. A 20 m diameter CO_2 FACE plot elevating the ambient atmospheric CO_2 concentration to 800 µmol mol^{-1} in a 3 m tall canopy with average ambient wind speeds of ~1.5 m s^{-1} would require 1,210 short tons of CO_2 per year (an average of 250 kg h^{-1}) if the enrichment was maintained every day during daylight hours. At a cost of $120 per short ton, CO_2 would cost $145,000 per plot per year. The annual thermal energy requirements to elevate the canopy temperature of a plot with the same dimensions by 4 °C were calculated following Kimball (2005, Eq. 14), using hourly weather data for the Konza Prairie, KS for 2007. Based on these calculations and an electric cost of $0.10 per kWh, the annual electricity cost for infrared heating would be $211,000 per year (Table 4).

Table 4. Estimated annual operating costs for an open field 2 x 2 complete block elevated temperature and elevated CO_2 interaction experiment with 20 m diameter plots (17m usable diameter) and five replicates.

Heat cost per plot per year @$0.1/kWh	$211,000
Heated plots per replicate	2
CO_2 cost per plot per year	$145,000
CO_2 enriched plots per replicate	2
Combined heat and CO_2 cost per replicate	$712,000
Number of replicates	5
Heating system maintenance	$10,000
CO_2 fumigation, storage and vaporization systems maintenance	$5,000
Annual materials and maintenance cost per site	$3,560,015
Site operations manager annual salary	$80,000
Site operations manager labor (FTE)	1
Site operations technicians annual salary	$45,000
Site operations technician labor (FTE)	2
Site operations labor cost	$170,000
Annual materials, maintenance and labor cost per site	$3,560,185

Treatment uniformity in an open field experiment

FACE facilities have consistently provided acceptable spatial and temporal uniformity of CO_2 and O_3 enrichment treatments over plot diameters up to 30 meters. The empirical standard for temporal uniformity for a FACE experiment has been the ability to provide a one minute average treatment level that is within 20% of the absolute target concentration for 80% of the treatment period. The flaw in this metric is that a large portion of the target concentration is provided by the ambient conditions. The closer the target concentration is to the ambient concentration, the easier it becomes to meet this treatment uniformity performance metric. The more appropriate metric is to compare the treatment variability to the treatment difference from the ambient baseline. In this case, the performance metric of percent deviation around the target concentration is independent of the relationship between the target concentration and the ambient background.

Most CO_2 FACE experiments have tried to maintain an absolute CO_2 treatment target of 500 to 600 µmol mol^{-1}, which is approximately 200 µmol mol^{-1} above ambient. 20% of 550 is 110, which is more than 50% of the treatment elevation. If we compare the relative variation of the concentration to the treatment elevation instead of the absolute target concentration, the performance metric will remain constant as the treatment elevation changes. This allows us to infer the treatment variability of a new FACE experiment using a different target value from prior experiments. Since most FACE experiments operated to date have demonstrated the ability to maintain the one minute average treatment concentration at the plot center to within 50% of the target elevation for greater than 80% of the time, we expect this experiment will also be able to achieve this performance metric. Since the target concentration of 800 µmol mol^{-1} is about 400 µmol mol^{-1} above ambient, we can expect that a 20 m diameter by 3 m tall FACE plot would have more than 80% of the one minute average concentration readings at the center of the plot within 200 µmol $mol^{-1}$of the 800 µmol mol^{-1} target.

Recent research into the effect of the FACE system fumigation design on spatial variability has shown the ability of the initial gas concentration as it leaves the emitters to affect spatial treatment uniformity, especially between the upwind edge and the rest of the plot (Lewin, et al. in press), but for any single design, the spatial variability at a 400 µmol mol^{-1} above ambient set point should have the same fractional relationship to the spatial variability in a similarly sized plot operating at a 200 µmol mol^{-1} above ambient. FACE sites that have examined spatial variability have usually reported long term spatial concentration averages within 50% of the treatment elevation value for the plot volume between the center of the plot and one to three meters from the plot edge, depending on the plot diameter, fumigation height and plant canopy, so a similar level of spatial variability is expected in this experiment.

Experiments using the temperature FACE (T-FACE) technology using infrared heaters have also studied temporal and spatial variability (Kimball, 2005, Kimball *et al*. 2008). Temporal variability is affected by wind speed and controller responsiveness. Spatial variability is affected by the thermal emission patterns of the infrared heaters and the heater positioning within and around the plot, canopy structure and plant condition. The amount of heat needed to warm an object depends on the object's heat absorbing properties and its ability to transfer intercepted energy into latent heat through evaporation of water in or on the object instead of converting it to sensible heat. Well watered, actively growing plants with open stomata will require more infrared energy to elevate their temperature to a target value than dormant, dry plants. In a diverse plant community, some species may heat more than others, introducing spatial temperature variability even if the infrared radiation is uniformly distributed. Temperature feedback from multiple thermometers strategically placed within the plot will be needed to minimize these sources of variability. The initial open field design proposed in this report includes four heating zones per plot, with at least four thermometers and four independent power controllers. Actual experience with the hardware will dictate whether more heating zones will be needed to reduce spatial and temporal variability. Bruce Kimball has developed heating models that describe the performance of infrared heaters on short plant canopies in small (3 - 5 m) diameter plots that should be expandable to larger areas (Fig. 7 and 8).

Figure 7. Theoretical distribution of the thermal radiation received on a plot surface from 24 groups (or nodes) of black-body flat plate heaters deployed in the hexagonal patterns depicted in Figure 6. The six center heater groups are at a height above the vegetation canopy of 4.8 m and they point nadir. Likewise, the six heater groups at a mid position between center and outside point nadir, and they are at a height of 4.0 m. The twelve heater groups around the periphery are at a height of 3.2 m, tilted at 45° from vertical, and pointed toward the center of the smaller hexagons. The vertical axis is the sum of angle factors from each of the 24 nodes to 20-cm pixels on the plot surface.

Figure and caption credit: Bruce Kimball

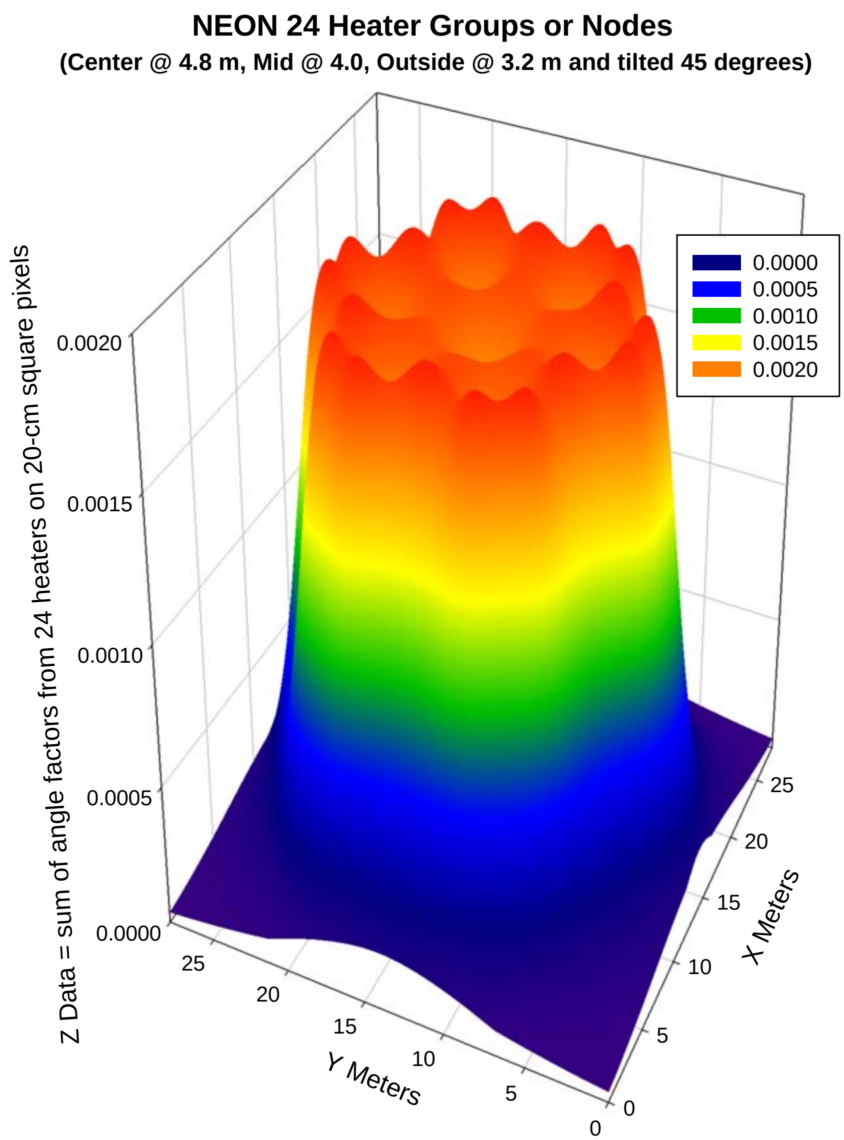
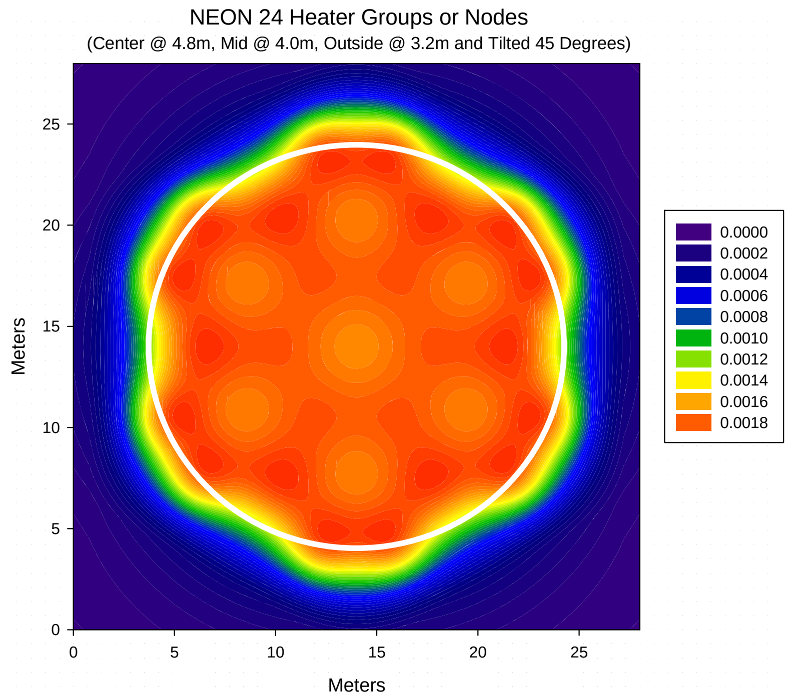


Figure 8. Two-dimensional color contour depiction of the theoretical distribution of the thermal radiation received on a plot surface from 24 groups (or nodes) of black-body flat plate heaters deployed in the hexagonal patterns depicted in Figure 6. The color code and the heights and orientations of the 24 heater groups are the same as in Figure 7. The white circle has a diameter of 20 m and indicates the border of the useable plot area.

Figure and caption credit: Bruce Kimball



Based on these models, it appears this new T-FACE design will be able to provide a uniform temperature treatment over the entire plot area. Exactly how uniform that treatment will be will require testing and probably some optimization to the control program and hardware design.

Influence of plot size on construction and operations costs

After performing the engineering and cost estimates for GCE facilities with individual usable plot areas of at least 225 m^2, the question was raised about the construction and operation expenses and usable plot areas of significantly smaller plots. Two possible sizes were requested, a 2 x 2 complete block experiment with 5 replicates with 8 m usable plot diameters, and the same experimental design with annual CO_2 and electrical operations costs of approximately $750,000. Since this request was made very late in the design and cost estimation process, we were not able to do as detailed cost estimates as for the prior designs. For many components we reviewed the cost estimates for the 20 m diameter plots and adjusted them as appropriate for smaller plots (Table 5). We were able to obtain a detailed energy analysis from Bruce Kimball for smaller plots (Appendix 2) and a price quote for the smaller infrared heaters, which comprise a major portion of an elevated temperature plot (Appendix 4). The number of infrared heaters and the annual electrical energy and CO_2 use estimates scale with plot area, so they showed marked reductions with changing the area from 227 m^2 to 6 m^2. The core control systems scale for the most part with plot number, which did not change. Other infrastructure needs partially scale with plot area and partly with number of plots, sometimes with a fixed base cost, so the effect of plot size on those components varied by individual component and were difficult to estimate in the short time available to do these calculations. Based on the estimates and analyses available, 8 m usable plot diameters will have an annual electric and CO_2 cost of $700,100 (Table 6). Scaling this cost to $750,000 per year yields plots with usable diameters of approximately 8.3 m. Other than electric and CO_2 use, most construction and operational expenses would not differ appreciably between 8.3 m and 8.0 m diameter plots, so we only present the cost comparisons between building and operating experiments incorporating 20 m and 8 m diameter plots.

Table 5. Estimated construction costs for an open field 2 x 2 complete block elevated temperature and elevated CO_2 interaction experiment with 10 m diameter plots (8 m usable diameter) and five replicates.

Materials cost per elevated temperature plot	$42,142
Number of elevated temperature plots per replicate	2
Materials cost per ambient temperature plot	$7,866
Number of ambient temperature plots per replicate	2
Materials cost per elevated CO_2 plot	$20,000
Number of elevated CO_2 plots per replicate	2
Materials cost for ambient CO_2 plot	$3,000
Number of ambient CO_2 plots per replicate	2
Materials cost per replicate	$146,016
Assembly labor cost per replicate	$8,160
Construction cost per replicate	$154,176
Number of replicates per site	5
Support equipment for IR plots	$3,970
Support equipment for CO_2 plots	$500
Central control center cost	$20,000
Central CO_2 storage and vaporization system cost	$200,000
Total experiment construction cost for 1 site	$995,350
Initial hardware engineering and programming labor	$200,000
Total cost	$1,195,350
Total plot area per treatment	393 m^2
Total area in all plots	1,571 m^2
Cost per square meter of total plot area	$761
Cost per square foot of total plot area	$71
Usable experimental area per treatment	251 m^2
Usable experimental area in all plots	1,005 m^2
Cost per square meter of usable experimental area	$1,189
Cost per square foot of usable experimental area	$110

Table 6. Estimated annual operating costs for an open field 2 x 2 complete block elevated temperature and elevated CO_2 interaction experiment with 10 m diameter plots (8 m usable diameter) and five replicates.

Heat cost per plot per year @$0.1/kWh	$33,760
Heated plots per replicate	2
CO_2 cost per plot per year	$36,250
CO_2 enriched plots per replicate	2
Combined heat and CO_2 cost per replicate	$140,020
Number of replicates	5
Heating system maintenance	$4,000
CO_2 fumigation, storage and vaporization systems maintenance	$2,000
Annual materials and maintenance cost per site	$706,100
Site operations manager annual salary	$80,000
Site operations manager labor (FTE)	1
Site operations technicians annual salary	$45,000
Site operations technician labor (FTE)	1
Site operations labor cost	$125,000
Annual materials, maintenance and labor cost per site	$831,100

A comparison of plot sizes to construction costs and operating costs shows the effect of plot size on the construction and annual operations budgets. For a 2 x 2 complete block design with 5 replicates, 20 m diameter plots (17 m usable diameter, 227 m^2 usable area) will cost $2,873,430 to design and build, which amounts to $633 per usable square meter of treated area (Table 3). With 10 m diameter plots (8 m usable diameter, 50 m^2 usable area) the equivalent construction cost is $1,195,350, which works out to $1,189 per usable square meter (Table 5). Annual operational costs are $3,560,015 to operate a site using 20 m diameter plots (Table 4) and $831,000 for 10 m plots (Table 6). Changing the design from 20 m to 10 m diameter plots, a 78% reduction in usable treated area, results in a 77% reduction in the annual operations cost but only a 58% reduction in the total construction cost. These ratios reflect the close relationship between plot size and electric and CO_2 demands, which are the dominant annual operating expenses, and the more decoupled relationship between plot size and construction costs. Expressed as cost per square meter of usable treated area, this reduction in plot size results in an 87% increase in construction costs and 5%increase in operations costs per unit of usable area.

Site characteristics for an open field temperature by CO_2 study

Experiments using open field treatment techniques work best when they are placed in locations with significant experimental area, smooth topography and uniform vegetation. A rough rule of thumb for CO_2 FACE plots is to have at least 3 plot diameters between the edges of an elevated treatment plot and adjacent elevated or ambient treatment plots. This separation reduces the CO_2 cross-contamination between plots, which improves CO_2 control and simplifies interpreting experimental results. We believe this amount of separation will be adequate for the temperature component as well. In the study described herein, an experimental site with 20 plots would need at least 9 ha of space. High soil or vegetation variability could markedly increase this value.

The smoothness of the topography and canopy uniformity affects CO_2 treatment temporal uniformity and CO_2 use. Relatively minor topological features and obstructions near the upwind side of a plot can markedly increase CO_2 use. At the FACTS-1 FACE facility, one plot located in a depression and near a forest edge uses up to twice the CO_2 compared to the other plots at this site. A similar, but smaller effect was noted at a Swiss FACE site where a tall forest edge was situated near one of the FACE plots.

With FACE technology, some ambient wind is necessary to move CO_2 through a plot, but once minimal winds (greater than ~0.5 m s^{-1}) are present, increased wind speeds and increased turbulence increase CO_2 use, which increases operational costs. Fortunately, many sites have average wind speeds within 1 to 1.5 m s^{-1}, which keeps CO_2 expenses within reason. Infrared heating demand is also affected by wind because of the moving air carrying away both heat and humidity, but this effect is not expected to be as large percentage-wise as for CO_2. In this study, the estimated heating cost is double the CO_2 cost, so wind related increases in heating costs could be noticeable. Bruce Kimball is doing further research on how climate parameters affect infrared heating of a plant canopy.

Climatic artifacts present in an open field experiment

The infrastructure used in open field infrared heating and CO_2 elevation will cause some shading in the treatment plots, on the order of 10%, but this will be less than the 20% or greater shading imposed when using greenhouse enclosures. Infrared heating of a plant canopy does not perfectly mimic global warming. Infrared heaters warm the plant and soil surfaces, as if the sun had become brighter. Global warming will increase the air temperature along with all other components of the environment. While infrared heating does not provide a perfect temperature treatment, other heating methods that provide direct heating of the air are too expensive to operate and have their own temperature gradient problems. With infrared heating of the canopy, the temperature gradient between the leaf and the air will be greater than what would naturally occur, which will cause a drop in relative humidity in the immediate vicinity of the leaf. This in turn will cause a larger vapor pressure deficit between the interior of the leaf and the surrounding air, which will increase transpiration more than would be expected with natural warming. This temperature gradient is present in sunlit leaves under ambient conditions. It will just be greater with infrared heating. One way to accommodate this effect is to calculate the additional transpiration due to the infrared heating and add sufficient water to make up that difference.

Open field CO_2 elevation has more short-term variability than occurs in nature due to the inability to perfectly mix the added CO_2 before it enters the plot and the natural diffusion as the CO_2 enriched parcel of air passes through the plot. As discussed above, the fractional variability of the added CO_2 treatment should be the same for an absolute 800 μmol mol^{-1} (400 μmol mol^{-1} above ambient) treatment as for a 200 μmol mol^{-1} above ambient treatment. Most research to date has indicated the short-term concentration variability will have minor effects on ecosystem functioning.

If the target CO_2 concentration is not set to track ambient diurnal and seasonal trends the CO_2 profile will not match the future reality. Tracking of ambient CO_2 concentration has not been given high priority in most current FACE experiments, but can be accomplished using current technology, and is being done at the FACTS-1 FACE facility.

Sensitivity analysis of cost estimates included in this report

The scope of treatment options changed as this work evolved. As a result, we have had to examine more options than originally intended and evaluate some designs that have only recently been envisioned and have never been built. While the expanded scope of this study resulted in decreased investigation into any single design, we still believe the cost estimates provided are well within the "rough order of magnitude" requested in the work plan. Greenhouse costs were based on discussions with greenhouse vendors and people who have built large greenhouse ranges or are currently soliciting bids to build greenhouses. Greenhouse construction cost estimates have been bracketed by high and low estimates that should cover the cost spread. With the open field design, we have used updates of prior CO_2 FACE site and infrared heating experiment construction and operations costs to define the estimates for the combined temperature and CO_2 experiment. These estimates were augmented by obtaining current price quotes for the more expensive components, such as the infrared heaters, CO_2 analyzers, meteorology sensors and flow control valves. The current quote for the infrared heaters comprises 70% of the construction budget estimate for the elevated temperature portion of the experiment, with the other component and energy prices coming from Bruce Kimball's current work building and designing temperature elevation experiments. The recent (within 6 months) quotes for wind speed and direction sensors, CO_2 gas analyzers and gas flow control valves cover 50% of the CO_2 exposure system estimate. These recent price quotes should constrain the differences between the estimates provided in this report and actual quotes obtained if the experiment moves towards implementation.

CO_2 costs are computed at $120 per US short ton. CO_2 cost is dependent on local market demands, transportation costs and source type. It is very variable across North America and can vary at an individual location depending on whether the CO_2 must come from geologic or fossil fuel sources to make use of non-current carbon isotope ratios or can come from fermentation plants. Electric costs are computed at $0.10 per kilowatt-hour. Both of these prices vary regionally and should be determined for each proposed location before drawing up a final operating budget.

References:

Chand, I and Bhargava, PK. 2005. Estimation of angle of deflection of rain at driving rain prone stations in India. Journal of Asian Architecture and Building Engineering**.** 4**,** 1: 223-229

Davies, PA. 2005. A solar cooling system for greenhouse food production in hot climates. Solar Energy 79: 661-668

Dempster, WF. 1999. Biosphere 2 engineering design. Ecological Engineering 13: 31-42

Kimball, B.A**.** 2005. Theory and performance of an infrared heater for ecosystem warming. *Global Change Biology* 11:2041-2056.

Kimball, B.A., M.M. Conley, S. Wang, X. Lin, C. Luo, J. Morgan, and D. Smith. 2008. Infrared heater arrays for warming ecosystem field plots. *Global Change Biology* 14:309-320.

Lewin, KF, Nagy, J, Nettles, WR, Cooley, DM, Rogers A. In press. Comparison of gas use efficiency and treatment uniformity in a forest ecosystem exposed to elevated [CO_2] using pure and pre-diluted Free Air CO_2 Enrichment technology. DOI: 10.1111/j.1365-2486.2008.01748.x

Appendices: Personal communications and price quotes:

Appendix 1: Scaling Infrared Heaters Arrays Up to 20-m Diameter for Use in NEON Open-Field Plots.
File name: Neon T-FACE V3.doc.
File date: October 27, 2008

Scaling Infrared Heaters Arrays Up to 20-m Diameter for Use in NEON (National Ecological Observatory Network) Open-Field Plots

by

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Summary

In order to meet the objectives of the National Ecological Observatory Network (NEON), there is a need to warm 20-m-diameter open-field plots by 4°C above current ambient temperatures. One promising technique would be to deploy infrared heaters over the plots, an approach that is being used successfully for 3-m plots and has been tested for 5-m plots. A promising design for deploying these heaters across the plot would be to nest seven 8-m hexagons within an overall 20-m hexagon. There would be 24 nodes at the points of the hexagons with a group of heaters at each node. Based on theoretical calculations, excellent uniformity of the distribution of thermal radiation could be achieved with six central nodes at an elevation of 4.8 m above the top of the vegetation canopy and pointed nadir, six mid-spaced nodes at an elevation 4.0 m and pointed nadir, and twelve nodes around the periphery tilted 45° and pointed toward the center of the smaller hexagons. An analysis of the geometry with respect to the distribution of the thermal radiation falling inside versus that lost outside the plot showed that such a 20-m plot should have higher "geometric efficiency" (58%) compared to the current 3-m plots (37%). An additional analysis of the convective losses from the heaters themselves showed that the larger heaters planned for this application (characteristic dimension of at least 450 mm) should enable a significantly greater "convective efficiency" compared to the presently used heaters (characteristic dimension of 60 mm). Using a theoretical equation with hourly weather data for the Konza Prairie and assuming the vegetation would have evapotranspiration and other characteristics similar to alfalfa 7 summer months of the year and be dormant for 5 winter months, hourly thermal radiation requirements were calculated. Then using efficiency equations from the prior 3-m plots and from the new analyses presented herein, heater power requirements were also calculated. Assuming the newer theoretical efficiency analysis is correct, an array with

72 8600-W heaters (3 per node) should be able meet the 4°C target warming about 94% and 99% of the day and nighttime hours, respectively. Solar shading would be about 10%. The annual power requirement for a 20-m-diameter plot with 72 such heaters under the given conditions would be about 2,110,000 kW-hr, which at an electricity price of $0.1 per kW-hr amounts to $211,000 per year per heated 20-m plot. The initial capital costs for such a heater array plus a reference plot with dummy heaters would probably be about $180,000.

Introduction and NEON Requirements

As communicated by Mr. Keith Lewin, Brookhaven National Laboratory, there is a need to warm free-air ecological field plots to determine the likely effects of global warming on various ecosystems for NEON, the National Ecological Observatory Network. In order to simulate ecological processes in a near-natural way, such plots need to be at least of 20-m scale, and to simulate the likely effects of global warming near the end of this century, the degree of warming in the plots needs to be controlled to be at least 4ºC above today's normal ambient temperatures.

We have previously achieved warming of open-field plots using a T-FACE (temperature free-air controlled enhancement) system on grazing land (Kimball *et al.*, 2008) and currently on wheat here at the U.S. Arid-Land Agricultural Research Center. Our current T-FACE system uses six 1000W infrared heaters deployed in a hexagonal pattern over 3-m-diameter (7.1 m^2) plots to warm the plant canopies by 1.5ºC during daytime and 3.0ºC at night. For a short time, we also tested the system over a 5-m-diameter plot, which is a near-tripling of the area (19.6 m^2) (Kimball and Conley, 2009). For this test we deployed eighteen of the 1000W heaters in a similar hexagonal pattern. For both the 3- and 5-m-diameter plots, excellent uniformity of the warming was achieved when the heaters were at a height of 0.4*diameter and were tilted at 45º from vertical and pointed toward the center of the plot. Moreover, the same equation was applicable for both plot sizes to calculate the efficiency (amount of downwelling thermal radiation from the heaters within the plot area per amount electrical energy input) from wind speed [efficiency (%) = $10 + 25e^{(-0.17u)}$, where u is wind speed at 2-m height ($m\ s^{-1}$)].

However, the NEON requirements represent a substantial increase in scale. A 20-m-diameter (314 m^2) plot has 44 times the area of a 3-m-diameter (7.1 m^2) plot, and 4ºC of warming is 2.67 times as much warming as the 1.5ºC we have been doing during daytime (when atmospheric turbulence is highest and when plant stomata are open so transpiration is generally occurring). In our experience under our Maricopa conditions, the $6000W/7.1m^2 = 845\ W/m^2$ of heater power is just marginal for achieving the desired 1.5ºC of daytime warming. Therefore, to achieve 4.0ºC of warming (under similar conditions and with heaters of similar efficiency), about 2300 W/m^2 will be required, which amounts to 708 kW for a 314 m^2 plot.

Heater Selection and Deployment

An infrared heater power requirement of 708 kW is huge in comparison to the size of commercially available infrared heaters, especially those whose thermal radiant properties are suitable for this plant-warming application (Kimball, 2005). Also, most commercially available heaters are only suitable for indoor use, and much effort would be required to water-proof them and make them safe and reliable for outdoor use. The Mor-FTE-1000 heaters[1] we have used previously (Kimball *et al.*, 2008; Kimball and Conley, 2009) could be used, but about 700 of them would be required, and even then considerable labor and high-temperature sealant is needed to make them safe for outdoor usage.

One candidate heater that might be used is a Raymax 1010 manufactured by Watlow Electrical Manufacturing Company (http://www.watlow.com/literature/specsheets/files/heaters/stl10100805.pdf), which is available in a totally liquid-tight model. The emitting surface is stated to have an emissivity very close to that of a black-body, and with an emittance of $10 W/in^2$ ($15.5 kW/m^2$), it should have excellent thermal radiant properties with almost no emission of energy at wavelengths that would be plant morphogenically active. The heaters are custom made to customer-specified sizes, but the largest they manufacture apparently is 8600W, 18 inches wide by 48 inches long (.457 m by 1.219 m = $0.557 m^2$). Thus, to achieve 708 kW, 82 such heaters would be required.

How should so many heaters be deployed over the plot to achieve adequate uniformity, high energy efficiency, and little solar shading? Compromises will be required to achieve all three objectives satisfactorily. One possibility would be to deploy six groups of 14 heaters each in a hexagonal pattern around the periphery in an extension of the approach used by Kimball and Conley (2009). The heaters would be deployed at a height of 0.4*20-m diameter = 8 m above the vegetative canopy, tilted at 45° from vertical, and pointed toward the center of the plot. If deployed horizontally over the plot, the total area of 84 of the Watlow heaters would be $46.8 m^2$, so solar shading would be about 15%. However, when tilted at 45°, and assuming only half would be shading because they're at the periphery, the solar shading would closer to 5%. About half the perimeter would have a heater above it.

[1] 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 U.S. Department of Agriculture.

Another scheme for deploying the heaters would be to erect seven smaller (8-m-diameter) arrays within the overall 20-m-diameter array, as suggested by Keith Lewin (Fig. 1). Many texts on the topic of heat transfer present theory on the exchange of thermal radiation between uniform black body surfaces (e.g., Gebhart, 1961; http://www.me.utexas.edu/~howell/). They show that the radiant emission, $q_{1\text{-}2}$ (W) from surface A_1 which goes directly to A_2 is $q_{1\text{-}2} = F_{12}W_1A_1$, where W_1 is the emissive power (W m^{-2}) of surface 1, A_1 is its area (m^2), and F_{12} is an angle or view factor that is dimensionless and depends solely on the geometrical orientation of the two surfaces with respect to each other. They show that in general the angle factor from an elemental area of surface 1 to an elemental area of surface two is $dF_{d1\text{-}d2} = (\cos\Theta_1 \cos\Theta_2)(\pi S^2)^{-1}dA_2$ where S is the length of the line from the surface 1 element to the surface 2 element, Θ_1 is the angle between S and the normal to surface 1, Θ_2 is the angle between S and the normal to surface 2, and dA_2 is the area of the element of surface 2 (e.g., Gebhart, 1961; http://www.me.utexas.edu/~howell/). By deriving equations to express S, $\cos\Theta_1$, and $\cos\Theta_2$, in terms of the distances from 20-cm-square pixels on the plot surface to heater surfaces at each of the nodes and then summing up the angle factors for all 24 nodes, I was able to calculate the theoretical distribution of thermal radiant energy from the array of heaters depicted in Fig. 1 over the whole 20-m plot, as well as areas outside the plot (Figs. 2 and 3).

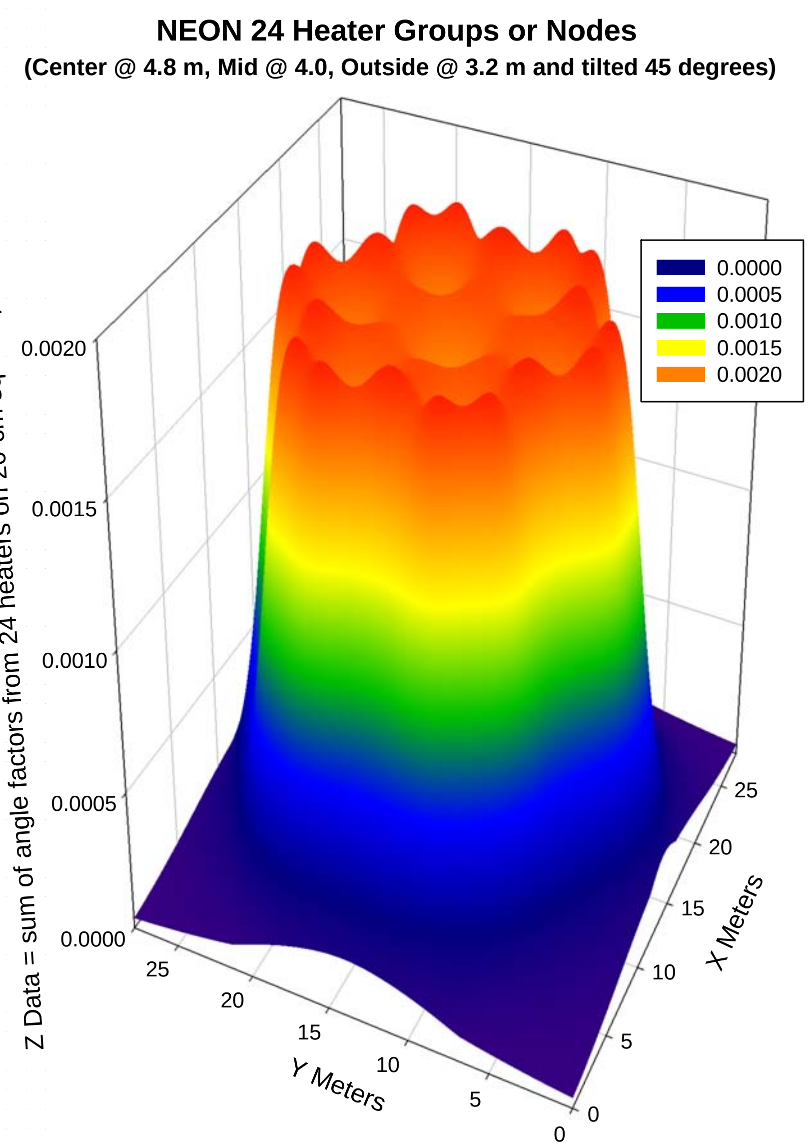
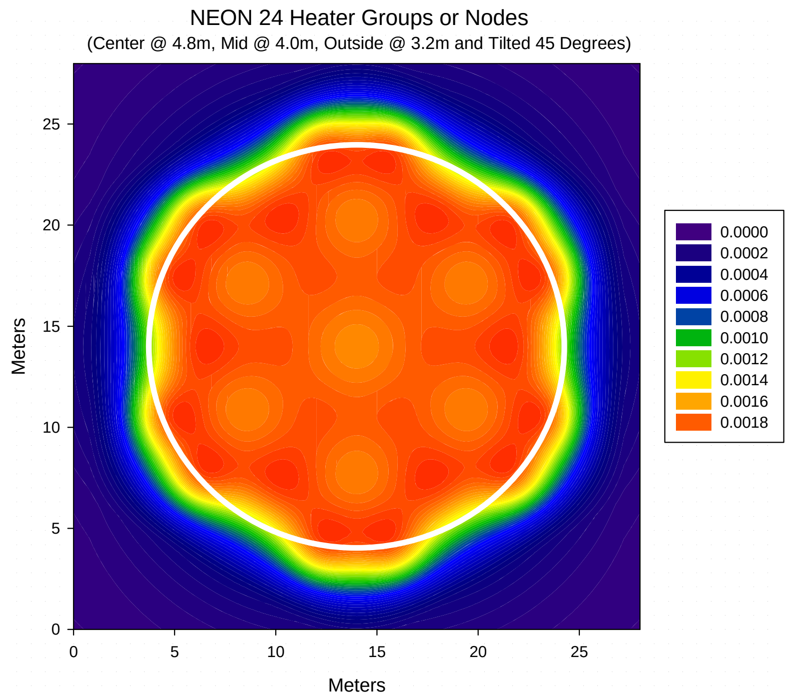


Figure 2. Theoretical distribution of the thermal radiation received on a plot surface from 24 groups (or nodes) of black-body flat plate heaters deployed in the hexagonal patterns depicted in Fig. 1. The six center heater groups are at a height above the vegetation canopy of 4.8 m and they point nadir. Likewise, the six heater groups at a mid position between center and outside point nadir, and they are at a height of 4.0 m. The twelve heater groups around the periphery are at a height of 3.2 m, tilted at 45° from vertical, and pointed toward the center of the smaller hexagons. The vertical axis is the sum of angle factors from each of the 24 nodes to 20-cm pixels on the plot surface.

Figure 3. Two-dimensional color contour depiction of the theoretical distribution of the thermal radiation received on a plot surface from 24 groups (or nodes) of black-body flat plate heaters deployed in the hexagonal patterns depicted in Fig. 1. The color code and the heights and orientations of the 24 heater groups are the same as in Fig. 2. The white circle has a diameter of 20 m and indicates the border of the useable plot area.



After calculating the distribution of thermal radiation for several test heights of the heaters, the configuration depicted in Figs. 1 and 2 was selected because it provides excellent uniformity. For this configuration, the six center heater groups are at a height of 4.8 m pointing nadir, the six mid heater groups are at a height of 4.0 m pointing nadir, and twelve outer heater groups are at a height of 3.2 m pointing toward the center of the small hexagons with a tilt of 45°. The coefficient of variation within the plot area is only 5.4%, which confirms that the uniformity of the theoretical distribution of the thermal radiation is excellent across the 20-m-diameter plot.

However, while the uniformity of the 24-node array in Figs. 1, 2, and 3 is excellent, solar shading is worse than that of the single hexagon used previously (Kimball *et al.*, 2008; Kimball and Conley, 2009). Deploying the center and mid heater groups horizontally and the outer groups at an angle of 45° and assuming that only half of the outer groups do shading, the overall solar shading would be about 10%.

Infrared Heater Efficiency

The efficiency of an infrared heater array is the amount of useful thermal radiant energy that falls within the plot area per amount of electrical energy input. Thus, the overall efficiency has two components: one accounts for the losses due to convection of energy away from the hot heater element by the wind or buoyancy (i.e., "convective efficiency"), and the other accounts for the losses due to thermal radiant energy falling outside the plot area (i.e. "geometric efficiency"). If an infrared heater is very close to the surface being warmed, then the geometric efficiency would approach 100%, whereas if a heater is raised to ever higher elevations above a plot, more and more radiation will fall outside the plot area, thereby lowering geometric efficiency. Furthermore, when the heaters are tilted away from nadir, more radiation can escape to the sky and potentially other areas outside the plot in the direction the heater is pointed, while in the back direction, less radiation will escape the useable area. Manufacturers of many models of infrared heaters add reflectors of various designs to try to reflect some of the thermal radiation that otherwise would be lost back toward the intended useable area and thereby improve geometric efficiency. The angle factor calculations for planer black bodies in the previous section do not include reflectors, so therefore, they are "worst cases," and opportunities may exist for improvements by adding reflectors. However, improvements in geometric efficiency with reflectors likely come at the cost of greater solar shading.

Based on the angle factor calculations described in the previous section, the theoretical "geometric efficiency" of the seven-hexagon configuration (Figs. 1, 2, and 3) should be about 58%. While 58% seems rather low, nevertheless it is considerably higher than the corresponding value of 37% calculated for a single hexagon with all the heaters tilted at 45° around the periphery (Kimball *et al.*, 2008; Kimball and Conley, 2009).

Kimball (2005) presented theory to predict the convective efficiency of infrared heaters based on convective heat transfer equations from Campbell (1977). The equations are based on prior work using flat plates in laminar flow, so real heaters in the more turbulent outdoors may have higher convective heat transfer coefficients and consequently somewhat lower efficiencies than the theoretical values. Nevertheless, the theory is useful for predicting approximate performance.

Table 1. Dimensions and other characteristics of various infrared heaters.

Manufact.[1]	**Model**	**Power**	**Shape**	**Length**	**Width**	**d**[2]	**Radiating Surface Material**	**Emis.**
		(W)		(mm)	(mm)	(mm)		
Kalglo	HS-2420	2000	rod	1510	8	8	incoloy	0.44[3]
Mor	ESES	250	disk	105	105	105	glaze[4]	0.96[5]
Mor	FTE	1000	rectangle	245	60	60	glaze[4]	0.96[5]
Watlow	Raymax[6]	8600	rectangle	1219	457	457	black paint	0.96[5]
Watlow	Raymax[6]	34400[7]	rectangle	1829[7]	1219[7]	1219[7]	black paint	0.96[5]

[1]Manufacturers' names are listed for the benefit of the reader and do not imply any special endorsement by the U.S. Department of Agriculture.
[2]d = characteristic dimension, which is the diameter of cylinders and disks or the shortest side of a rectangle for use in convection equations from Campbell (1977).
[3]Emissivity from Kimball (2005).
[4]Ceramic coated with glaze.
[5]Emissivity from manufacturers' claims.
[6]Specifically liquid-tight Raymax 1010.
[7]Bank of four of the Watlow 457 mm by 1219 mm infrared heaters adjacent to each other.

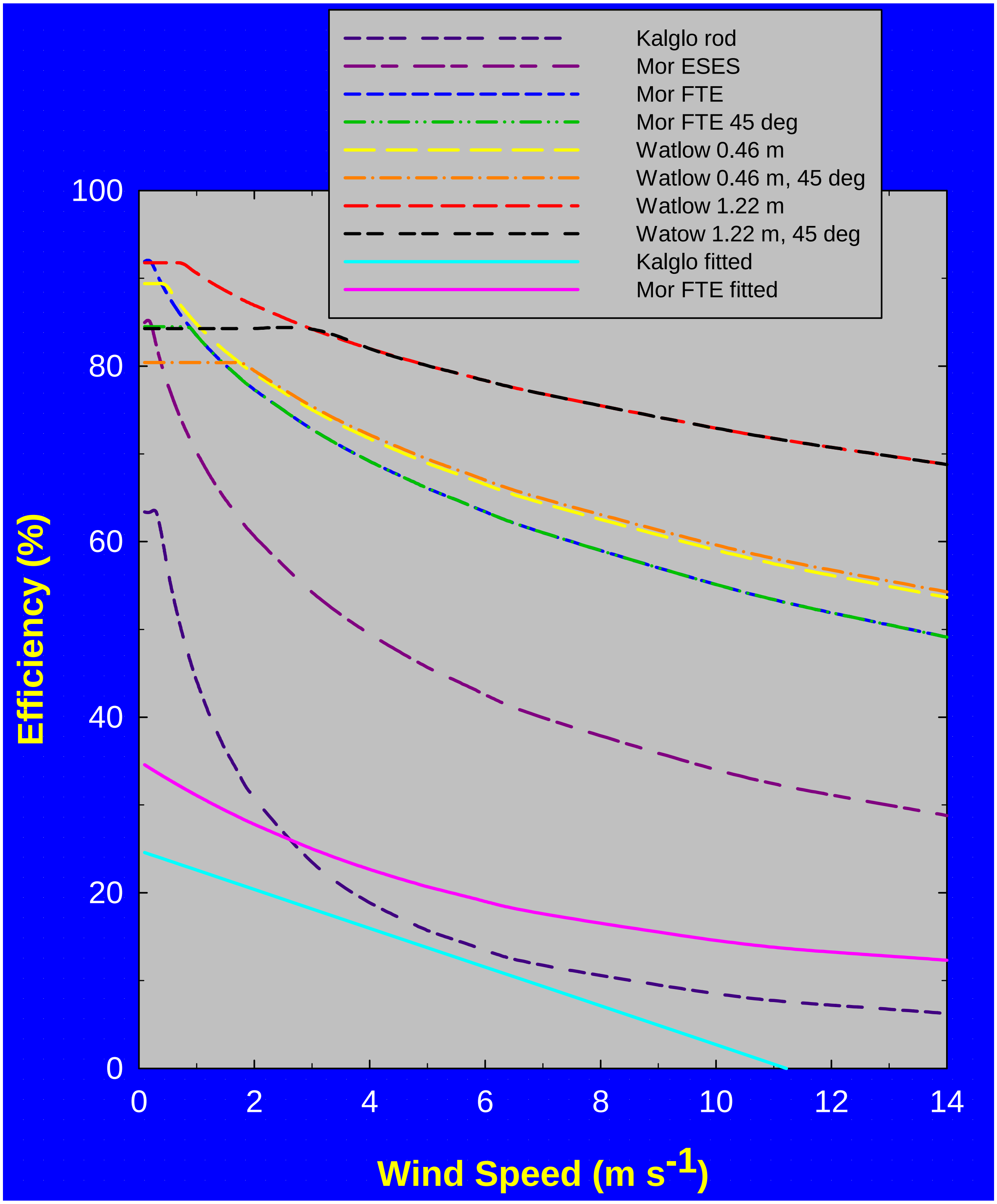


Figure 4. Theoretical convective efficiencies of several infrared heaters calculated using the theory derived by Kimball (2005). The characteristics of the heaters are listed in Table 1. The theory is based on flat plate equations from Campbell (1977) for air at 20°C and 100 kPa pressure. For heaters tilted at 45°, the coefficient for free-convection at low wind speed was assumed to be the same as that of a heated plate facing upward, whereas for heaters pointed down, the coefficient was one half that of an upward facing plate. The Kalglo fitted line is the measured overall efficiency of a Kalglo infrared heater (Kimball, 2005), and similarly the Mor-FTE fitted curve is the measured overall efficiency of a hexagonal array of Mor-FTE infrared heaters deployed over a 3-m-diameter plot (Kimball *et al.*, 2008).

Huge differences in theoretical convective efficiency exist among various designs of infrared heaters (Fig. 4). Because of the small characteristic dimension of the rod-shaped Kalglo heater and its low emissivity, its theoretical convective efficiency is the lowest among the several heaters examined. On the other hand, it has a large effective reflector housing, so that it is geometrically efficient, yet the resultant overall efficiency is still quite low as indicated by measurements [turquoise line in Fig. 4 from Kimball (2005)]. Looking at the theoretical curves for the other heaters in Fig. 4, it is apparent that increasing emissivity and increasing the characteristic dimension greatly improves the efficiency. A comparatively large 1.2 x 1.8 m heater from Watlow (actually 4 adjacent 1.2 x 0.46 m heaters) oriented nadir would have convective efficiencies ranging from about 93 to 69% for wind speeds from 0 to 14 m s^{-1}.

However, the theoretical convective efficiencies in Fig. 4 do not account for thermal radiation that falls outside the plot area, i.e. the geometric efficiencies. The geometric efficiencies for single hexagonal arrays of Mor-FTE infrared heaters (Kimball *et al.*, 2008) and of 24-node coupled hexagonal arrays (Fig. 1) are plotted as lines in Fig. 5. Also shown in Fig. 5 are the overall (geometric times convective) efficiencies of the two types of arrays. The theoretical overall efficiency of the single hexagonal array of Mor-FTE heaters is close to that of measured curve for 3-m-diameter plots (Kimball *et al.*, 2008), as well as 5-m plots (Kimball and Conley, 2009). This agreement with measured data gives confidence for using the theoretical curves.

The overall efficiency of a 20-m-dimater, 24-node connected infrared heater array of large Watlow heaters (Fig. 1) ought to be considerably higher than the overall efficiency of a single 3-m-diameter hexagonal array (Fig. 5). At zero wind, the efficiency increase should be from about 32 to 47% and at a high wind of 14 m s^{-1}, the increase should be from about 18 to 32%. Such an increase in efficiency implies that 3 heaters per node should be sufficient rather than four for a total of 72 heaters rather than 96.

Thermal Radiation and Electrical Power Requirements

Kimball (2005) derived an equation that predicts the amount of additional thermal radiation required to warm a plant canopy as a function of microclimatic and plant parameters, and in the previous section, the efficiencies of infrared heater systems were addressed. From the radiation requirement and the efficiency, the amount of electrical power per m^2 of ground area and degrees of warming can be calculated. However, plant canopies vary immensely in their architecture, and their stomatal conductance changes drastically from night to day and, at least for temperate climates, from summer to winter. Further, the microclimatic variables, among which wind speed is especially important, are continually changing from night to day and from one weather pattern to another. Therefore, the cost of an infrared warming treatment in a proposed NEON experiment will depend greatly on site selection and the vagaries of weather.

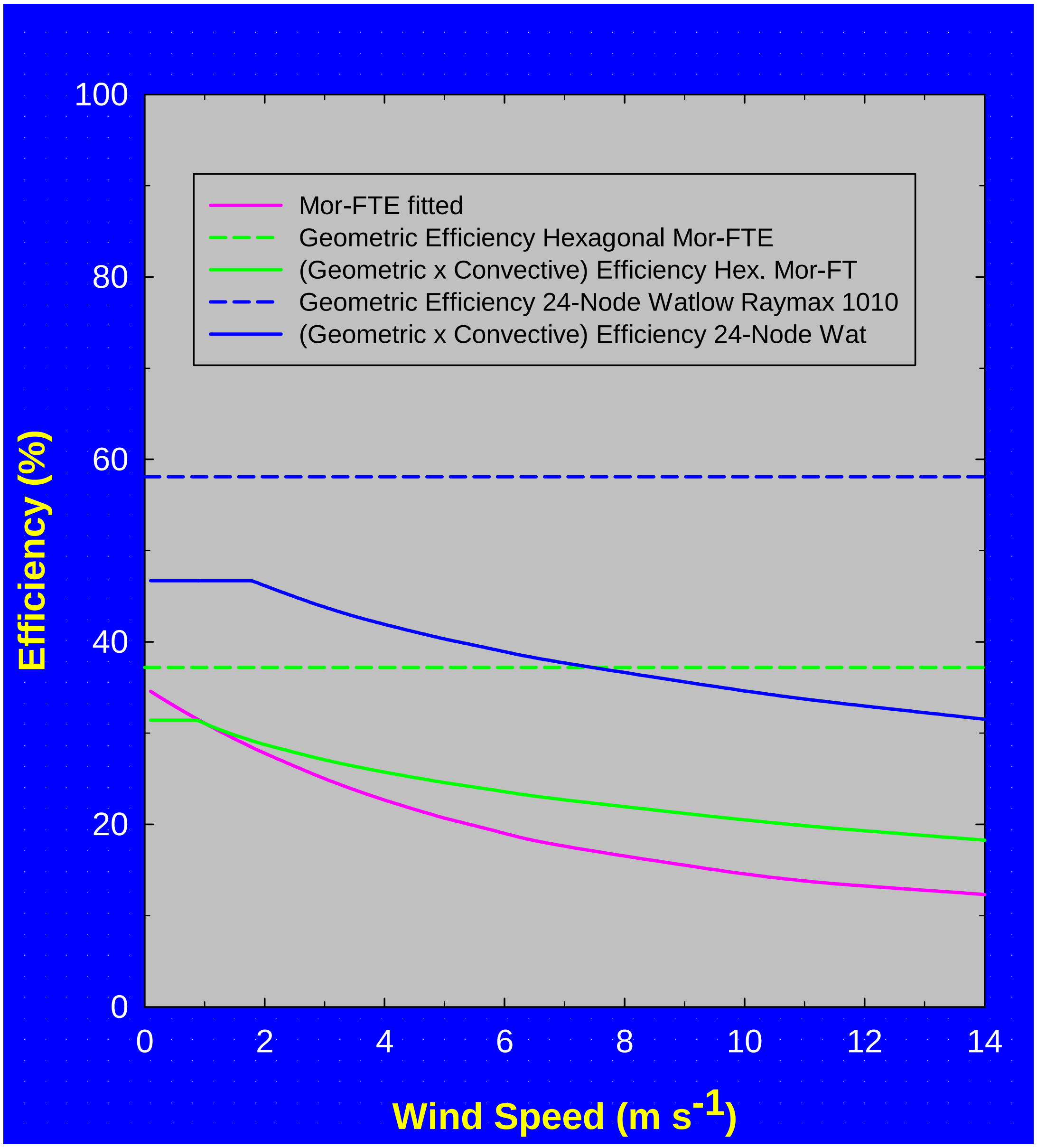


Figure 5. Geometric efficiencies of single hexagonal arrays of Mor-FTE infrared heaters and of 24-node connected hexagonal arrays shown in Fig. 1. Also shown are the total (geometric times convective) efficiencies for the two types of arrays. The Mor-FTE fitted curve is the measured overall efficiency of hexagonal arrays of Mor-FTE infrared heaters deployed over 3-m-diameter plots (Kimball *et al.*, 2008).

Nevertheless, some assumptions can be made from which estimates of electrical power can be calculated. First, the Konza Prairie has been mentioned as at least one site for NEON. Therefore, the following assumptions were made: (1) The architecture and stomatal characteristics are similar to those of 0.5-m-tall alfalfa for which standardized equations exist for predicting evapotranspiration (Allen *et al.,* 2005), and (2) that the vegetation is actively growing and non-water-stressed during the months from April through October and is dormant from November through March. Then, using hourly weather data for 2007 that was downloaded from the Konza Prairie Web site (http://www.konza.ksu.edu/data_catalog/meteoro/) along with the overall efficiency curve for a 24-Node array (Figs. 1 and 5), following Kimball (2005; Eq. 14) and Kimball *et al.* (2008), infrared heater electrical power requirements were computed (Fig. 6).

The most striking feature of the frequency curves of the heater power requirements (Fig. 6) is the large spike for the night, 24-node efficiency curve at about 50 W m^{-2} C^{-1}. However, this is probably not real but rather is likely an artifact of the researchers assigning a constant 0.41 m s^{-1} wind speed under calm conditions when their anemometers stalled. Nevertheless, the cumulative fractions are most useful for this analysis and this spike (as well as one night, 6-node efficiency) at very low wind speeds do not affect the annual power requirement estimates. As expected from the general tendency for there to be more turbulence and higher wind speeds during daytime, the frequency curves for daytime have broader peaks and extend to much higher power requirement values compared to nighttime. Most importantly, the higher efficiency of the 24-node array led to a large shift of the curves to lower power requirements compared to the curves for the 6-node efficiency.

The cumulative fraction curves (Fig. 6) are most useful for estimating the percentage of the time that various heater combinations can meet the desired 4˚C warming target. The vertical dotted line at 493 W m^{-2} C^{-1} in Fig. 6 corresponds to the unit heater capacity for 72 8600-Watt Watlow infrared heaters deployed over the 314 m^2 plot with 4˚C of warming. The horizontal dotted lines indicate where the 493 line crosses the daytime cumulative fraction curves for 6-node and 24-node efficiencies, respectively. Following these horizontal lines to the right axis, the cumulative fractions of the daylight hours that this 72-heater array can meet the 4˚C target are 0.57 and 0.94 for the 6-node and 24-node efficiencies, respectively. In other words, 72 of the 8600-watt Watlow heaters can meet the requirement 57% of the daylight hours if we assume that the efficiency of the array is no better than that observed previously with 3-m arrays (Kimball *et al.*, 2008). On the other hand, if we assume that the newly predicted overall efficiency for a 24-node array is correct (Fig. 5), then the same 72-heater array should be able to meet 94% of the daytime heating requirements.

Using Fig. 6, the percentages of time that arrays with 48, 72, and 96 of the 8600-watt Watlow heaters in a 24-node array (Fig. 1) can meet the 4˚C heating requirement were estimated (Table 2). If the efficiency curve for the 6-node, 3-m-dimeter is applied for this much larger 24-node, 20-m-diameter plot, it appears that 48, 72, and 96 heaters could only meet the requirements only 32, 57, and 76% of the daylight hours, respectively. On the other hand, if the 24-node efficiency curve is assumed, the heating requirement should be met 72, 94, and 99% of the daylight time. For nighttime, all the heater combinations can meet the requirements at least 78% of the time even if the 6-node efficiency is assumed.

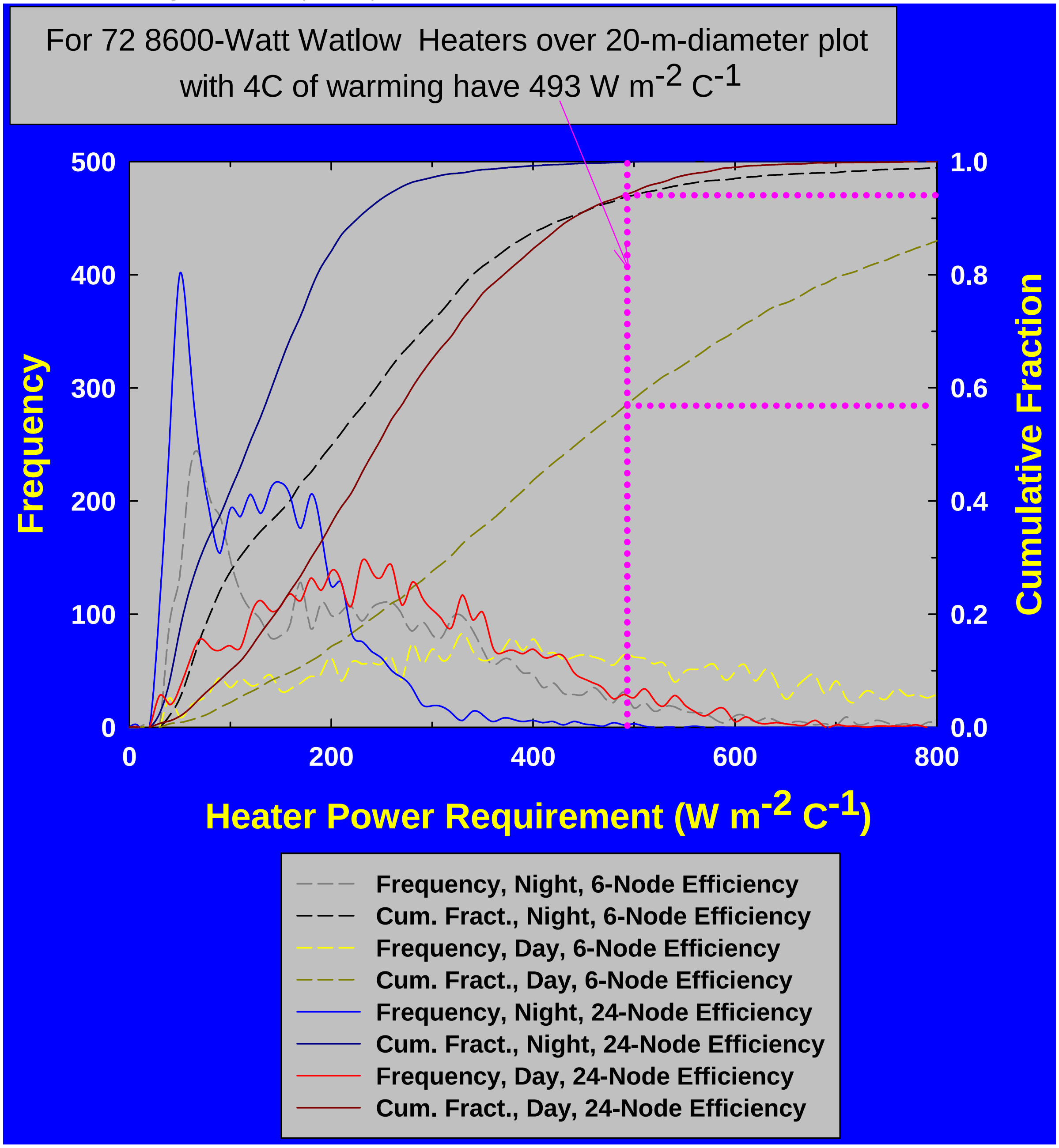


Figure 6. Frequency and cumulative fractions of hourly electrical power requirements for 24-node infrared heating of a 20-m-diameter open-field plot (Fig. 1) using 2007 weather data from Konza Prairie, KS, for separate night and daytime conditions. Two efficiency equations were used: (1) the equation from Kimball *et al.* (2008) for a 6-node, 3-m-diameter single hexagonal array with the heaters around the periphery and (2) the overall equation from Fig. 5 for a 24-node, 20-m-diameter 7-hexagon array (Fig. 1). The vegetation properties were those of 50-cm-tall alfalfa (Allen *et al.*, 2005) assuming no water stress (i.e., maximum evapotranspiration) during the months of April through October and dormancy from November through March. The dotted lines indicate that 72 8600W Watlow heaters deployed over the 20-m plot with 4C of warming amounts to 493 W m^{-2} C^{-1}, which means that the array should meet the daytime heating requirement about 94% of the daylight hours if the efficiency equation from Fig. 5 is correct or only about 58% of the daytime hours if the array were only as efficient as that of Kimball *et al.* (2008).

Table 2. Percentages of time that target degrees of warming (4°C) can be met for 24-node, seven-hexagon infrared heater arrays with deployment of 48, 72, or 96 8600-W Watlow heaters assuming that the efficiency of the array is the same as that determined by Kimball *et al.* (2008) for single hexagonal arrays (6-node) or is that predicted by the overall efficiency curve from Fig. 5 for a 24-node array. Also presented are the estimated annual electrical energy requirements and their corresponding costs. The computations were made with hourly weather data for 2007 for the Konza Prairie, KS with the 6-node and 24-node efficiencies applied to thermal energy requirements calculated following Kimball (2005, Eq. 14).

	Efficiency	
Item	**6-node[1]**	**24-node[2]**
Percentage of time target (4°C) heating can be met (%)[3]		
During daytime		
For 96 heaters	76	99
For 72 heaters	57	94
For 48 heaters	32	72
During nighttime		
For 96 heaters	98	100
For 72 heaters	94	99
For 48 heaters	78	98
Annual electrical energy requirement (kW-hr per plot)		
For unlimited heater capacity	3,920,000	2,120,000
For 96 heaters[4]	3,600,000	2,120,000
For 72 heaters[4]	3,270,000	2,110,000
For 48 heaters[4]	2,670,000	1,970,000
Annual power cost[5] ($ per plot)		
For unlimited heater capacity	392,000	212,000
For 96 heaters[4]	360,000	212,000
For 72 heaters[4]	327,000	211,000
For 48 heaters[4]	267,000	197,000
Extrapolated from prior 3-m plot experiments[6]	275,000	-

[1]Efficiency equation from Kimball *et al.* (2008) for single hexagonal array with all heaters around the periphery.

[2]Efficiency equation from overall curve for 24-node array from Fig 5.

[3]From Fig. 6 where the unit power requirement was calculated from:

$(\text{number of heaters})(8600\text{W})(314\ \text{m}^2)^{-1}(4°\text{C})^{-1}$

which equals 657, 493, and 238 W m^{-2} C^{-1} for 96, 72 and 48 heaters, respectively.

[4]8600 Watts each.

[5]At 0.1$ per kW-hr.

[6]Assumed (1) that the efficiency of the 20-m-array will be that of the 3-m-arrays, (2) that the power usage will be about 11.5 kW-hr/day/m^2 (Table 3) x (4.0/1.5) for 4°C of warming x 314 m^2 = 9629 kW-hr/day per 20-m-diamber plot for actively growing vegetation, (3) that half as much is needed when the vegetation is dormant, and (4) that the vegetation is active for 7 months per year and dormant 5 months per year.

Following the methodology described in the previous section, the total annual electrical power requirements were calculated assuming unlimited heater capacity for both the 6-node and 24-node efficiency assumptions (Table 2). However, for some of the time, especially under windy conditions, the heaters will be fully on and yet unable to meet the heating requirements, so the actual power consumed will be only that of the heater capacity. Therefore, the power requirements were calculated for the heater capacities corresponding to 48, 72, and 96 of the 8600-W Watlow heaters (Table 2). As expected, the power requirements go down with deceasing number of heaters. However, the most dramatic differences are between the efficiency assumptions.

Electrical Power Operating Costs

Electrical power prices vary region by region and even by time of day, but often are close to $0.1 per kW-hr. Under this price assumption, the annual electrical energy requirement values (Table 2) were multiplied by 0.1 to estimate annual power costs (Table 2). Assuming the 6-node efficiency, annual power costs likely will be on the order of $267,000, 327,000, or $360,000 per 20-m plot for 48, 72, and 96 heater arrays, respectively.

The energy requirement values in Table 2 were calculated using Konza Prairie weather and vegetation characteristics of alfalfa, and so the question arises as how accurate they can be. While no one has yet constructed an infrared heater array like that in Fig. 1, several groups have gained experience with smaller 3-m-diameter arrays. Table 3 lists observations of energy use from three such sites where infrared heater array experiments are underway. If we assume (1) that the efficiency of the 20-m-array conservatively will be no higher than that of the 3-m-arrays, (2) that the power usage will be about 11.5 kW-hr/day/m^2 (Table 3) x (4.0/1.5) for 4°C of warming x 314 m^2 = 9629 kW-hr/day per 20-m-diamber plot for actively growing vegetation, (3) that half as much is needed when the vegetation is dormant, and (4) that the vegetation is active for 7 months per year and dormant 5 months per year, then the annual power usage would be about 2,750,000 kW-hr per heated plot. At an electrical power price of $0.1/kW-hr, therefore, the annual operating cost for electricity would be on the order of $275,000 per heated 20-m-diameter plot (last line of Table 2). Thus, an extrapolation of the observed power use from these other systems is consistent with the totally theoretical calculations under the assumption that the efficiency is no better than that of the 6-node, 3-m arrays.

However, based on the analyses in previous sections, we have reason to believe that the geometric efficiency will be higher with the larger plot size and that the convective efficiency will be higher with larger characteristic dimensions of the heaters themselves. Therefore, assuming the 20-m, 24-node efficiency is more correct, the annual power costs are likely to be about $197,000, $211,000, and $212,000 for 48, 72, and 96 heater arrays.

I am cautiously optimistic that the 24-node efficiency curve from Fig. 5 is close to correct. Therefore, the 24-node design (Fig. 1) with 72 of the 8600-W Watlow heaters combination appears most promising.

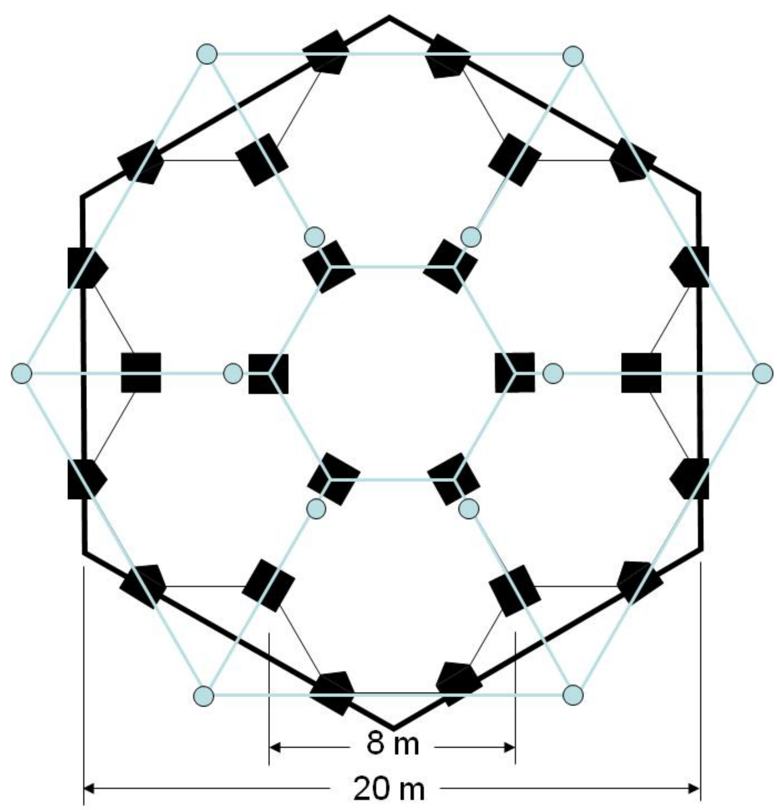
Table 2. Energy consumption and power costs for 3-m-diameter hexagonal arrays of Mor-FTE 1000W infrared heaters over grazing land at Haibei, China and Cheyenne, WY and over wheat at Maricopa, AZ. The power price is estimated to be \$0.1/kW-hr. The Maricopa data include an air conditioned trailer and an irrigation pump, and they are based on times when the wheat was actively growing.

Item	**Haibei** (1.2/1.7°C)	**Cheyenne** (1.5/3.0°C)	**Maricopa** (1.5/3.0°C)
kW-hr/day/m^2	8.2	11.3	11.8
kW-hr/day/plot	58	80	84
kW-hr/yr/plot	21,000	29,000	31,000
\$/yr/plot	\$2,100	\$2,900	\$3,100

Initial Capital Costs

In order to determine the initial capital investment, a determination must be made with regard to what structure would be required to deploy the heaters as depicted in Figs. 1, 2, and 3. More engineering is desirable, but one possibility is the use of 2" (50 mm) posts with 1½" (38 mm) cross members held together with Kee Klamps (e.g., http://www.simplifiedbuilding.com/products/1-kee-klamp.html) as indicated in Fig. 7.

Figure 7. Schematic diagram of structure to deploy the infrared heaters shown in Fig. 1. The circles are vertical posts from 2" (50 mm) pipe. The cross members are 1½" pipe (38 mm) all held together by Kee Klamps. The outer pipes are at an elevation to deploy the outer heaters at an average 3.2 m height above the vegetative canopy and tilted 45°. The pipes that go from outside to inside are angled at 45° so as to deploy the mid heaters at 4.0 m and the center heaters at 4.8 m. The inner hexagon of pipes is needed to tie the structure together and provide strength.



We previously noted that such a 24-node array (Fig. 7) with 72 heaters should have adequate capacity to warm the plot to the target 4˚C most of the time (Table 2). Here we also note that 72 heaters per 24 nodes means 3 heaters per node, which is advantageous for 3-phase wiring.

The construction cost for a 20-m-diameter infrared heater array with 72 Watlow liquid-tight infrared heaters plus that for a corresponding reference plot is likely to be about $180,000 (Table 4). However, the uncertainties surrounding the costs for the electrical load center and associated connectors and cabling are high.

Table 4. Estimated construction cost for 20-m-diameter plot warmed with 72 Watlow liquid-tight infrared-heaters plus that for corresponding reference plot with dummy heaters.

E:\Experiments\IR Heater\NEON\[NEON Parts list 20 m dia 24 nodes 72 heaters V2.xls]Detailed						
Parts and Equipment list for 20-m hexagonal infrared heated plot						
plus similar reference plot with dummy heaters						
Has 24 nodes defining 7 interior 8-m hexagons.						
Heaters at inner 6 nodes are at 4.8-m height and pointed nadir.						
Heaters at mid 6 nodes are at 4.0-m height and pointed nadir.						
Heaters around outside are at 3.2-m height and pointed 45 deg from horizonatal toward center of their respective inner hexagon.						
Has 72 8600W, 480V Watlow Liquid-tight heaters. Total of 620 kW, 480V, 1300 amps						
Item	**Approx. Cost Each US$**	**No. per plot**	**Cost per plot US$**	**No. plots**	**Total No. needed**	**Total cost $US**
For heated plot						
Flat Radient Panel Liquid-Tight 8600W 480V Heaters [Watlow Raymax 1010 (18"x48")]	1400	72	$100,800	1	72	$100,800
Mounting hardware	100	72	$7,200	1	72	$7,200
Dimmers (Watlow)	15000	1	$15,000	1	1	$15,000
Enclosure for dimmers, circuit breakers, etc	2000	1	$2,000	1	1	$2,000
Load Center	10000	1	$10,000	1	1	$10,000
Cabling and connectors	10000	1	$10,000	1	1	$10,000
Posts (2" pipe - 20 ft sections)	40	12	$480	1	12	$480
Kee Klamps at outer posts (3 at each post, 2" x 11/2" Tees)	22	18	$396	1	18	$396
Kee Klamps at outer posts (1 at each post, 11/2" swivel Tees)	19	6	$114	1	6	$114
Kee Klamps at middle posts (1 at each post, 2 x 11/2" Tees)	22	6	$132	1	6	$132
Kee Klamps at middle posts (1 at each post, 11/2" swivel Tees)	19	6	$114	1	6	$114
Pipe from outer post to past inner posts (26 ft 11/2")	40	6	$240	1	6	$240
Pipe from outer post to outer post (40 ft 11/2")	60	6	$360	1	6	$360
Pipe from inner post to inner posts (13 ft 11/2")	20	6	$120	1	6	$120
Kee Klamps if needed to couple to make 40 ft (11/2 couplings)	13	6	$78	1	6	$78
Kee Klamps at center joints (11/2" tee)	12	12	$144	1	12	$144
Kee Klamps at center joints (11/2" swivel tee)	19	12	$228	1	12	$228
Infrared thermometer (Apogee IRR-PN; four per 20-m plot)	600	4	$2,400	1	4	$2,400
PVC housing for IRT (home-made)	20	2	$40	1	2	$40
4 conductor cable	0.2	120	$24	1	120	$24
		Subtotal =	**$149,870**			**$149,870**
For reference plot						
Dummy Heaters (use sheet metal)	200	72	$14,400	1	72	$14,400
Mounting hardware	100	72	$7,200	1	72	$7,200
Posts (2" pipe - 20 ft sections)	40	12	$480	1	12	$480
Kee Klamps at outer posts (3 at each post, 2" x 11/2" Tees)	22	18	$396	1	18	$396
Kee Klamps at outer posts (1 at each post, 11/2" swivel Tees)	19	6	$114	1	6	$114
Kee Klamps at middle posts (1 at each post, 2 x 11/2" Tees)	22	6	$132	1	6	$132
Kee Klamps at middle posts (1 at each post, 11/2" swivel Tees)	19	6	$114	1	6	$114
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Pipe from inner post to inner posts (13 ft 11/2")	20	6	$120	1	6	$120
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Kee Klamps at center joints (11/2" tee)	12	12	$144	1	12	$144
Kee Klamps at center joints (11/2" swivel tee)	19	12	$228	1	12	$228
Infrared thermometer (Apogee IRR-PN; four per 20-m plot)	600	4	$2,400	1	4	$2,400
PVC housing for IRT (home-made)	20	1	$20	1	1	$20
		Subtotal =	**$26,426**			**$26,426**
For whole experiment						
Black body calibrator (Everest Interscience 1000?)	930	1	$930	1	1	$930
Portable handheld infrared thermometer? (Everest Interscience 100.3ZL?)	3040	1	$3,040	1	1	$3,040
		Subtotal =	**$3,970**			**$3,970**
		Total =	**$180,266**			**$180,266**

References

Allen, R.G., Walter, I.A., Elliott, R.L., Howell, T.A., Itenfisu, D., Jensen, M.E., and Snyder, R.L. 2005. *The ASCE Standardized Reference Evapotranspiration Equation*. American Society of Civil Engineers, Reston, VA. 195 pp.

Campbell, G.S. 1977. *An Introduction of Environmental Biophysics*. Springer-Verlag New York, Inc., New York, NY. 159 pp.

Gebhart, B. 1961. *Heat Transfer*. McGraw-Hill Book Company, Inc. New York. 454 pp.

Kimball, B.A**.** 2005. Theory and performance of an infrared heater for ecosystem warming. *Global Change Biology* 11:2041-2056.

Kimball, B.A., M.M. Conley, S. Wang, X. Lin, C. Luo, J. Morgan, and D. Smith. 2008. Infrared heater arrays for warming ecosystem field plots. *Global Change Biology* 14:309-320.

Kimball, B.A., and M.M. Conley. 2009. Infrared heater arrays for warming field plots scaled up to five meters diameter. *Agricultural and Forest Meteorology* (in press).

Appendix 2: Scaling Infrared Heaters Arrays Up to Larger Diameters for Use in NEON Open-Field Plots: Consideration of 20 and 8-m Diameters
File name: NEON T-FACE 20 & 8m V4.doc.
File date: November 16, 2008

Scaling Infrared Heaters Arrays Up to Larger Diameters for Use in NEON (National Ecological Observatory Network) Open-Field Plots

by

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Summary

In order to meet the objectives of the National Ecological Observatory Network (NEON), there is a need to warm relatively large open-field plots by 4°C above current ambient temperatures. One promising technique would be to deploy infrared heaters over the plots, an approach that is being used successfully for 3-m plots and has been tested for 5-m plots. A promising design for deploying these heaters across the plot would be to nest seven 8-m hexagons within an overall 20-m hexagon. There would be 24 nodes at the points of the hexagons with a group of heaters at each node. Based on theoretical calculations, excellent uniformity of the distribution of thermal radiation could be achieved with six central nodes at an elevation of 4.8 m above the top of the vegetation canopy and pointed nadir, six mid-spaced nodes at an elevation 4.0 m and pointed nadir, and twelve nodes around the periphery tilted 45° and pointed toward the center of the smaller hexagons. An analysis of the geometry with respect to the distribution of the thermal radiation falling inside versus that lost outside the plot showed that such a 20-m plot should have higher "geometric efficiency" (58%) compared to the current 3-m plots (37%). An additional analysis of the convective losses from the heaters themselves showed that the larger heaters planned for this application (characteristic dimension of at least 450 mm) should enable a significantly greater "convective efficiency" compared to the presently used heaters (characteristic dimension of 60 mm). Using a theoretical equation with hourly weather data for the Konza Prairie and assuming the vegetation would have evapotranspiration and other characteristics similar to alfalfa 7 summer months of the year and be dormant for 5 winter months, hourly thermal radiation requirements were calculated. Then using efficiency equations from the prior 3-m plots and from the new analyses presented herein, heater power requirements were also calculated. Assuming the newer theoretical efficiency analysis is correct, an array with 72 8600-W heaters (3 per node) should be able meet the 4°C target warming about 94% and 99% of the day and nighttime hours, respectively. Solar shading would be about 8%. The annual

power requirement for a 20-m-diameter plot with 72 such heaters under the given conditions would be about 2,110,000 kW-hr, which at an electricity price of $0.1 per kW-hr amounts to $211,000 per year per heated 20-m plot. The initial capital costs for such a heater array plus a reference plot with dummy heaters would probably be about $180,000.

In the event the operating costs for the desired 20-m-dimeter plots are unaffordable, one option would be to use a smaller plot size, say 8-m diameter. The nested seven-hexagon design with 24 nodes proposed for 20-m plots could also be scaled to 8-m, with the smaller hexagons being 3.2 m across. The six central nodes would be at an elevation of 1.92 m above the top of the vegetation canopy and pointed nadir, six mid-spaced nodes would be at an elevation 1.6 m and pointed nadir, and twelve nodes around the periphery would be at 1.28 m height, tilted 45°, and pointed toward the center of the smaller hexagons. This configuration would have the same high geometric efficiency (58%), and solar shading would be about 8%. Selecting heaters with the same characteristic dimension (0.46 m) as those used for the 20-m plot analysis, the overall convective time geometric efficiency should be the same. On this basis 24 such heaters with 3960 W capacity should be able to meet the heating requirements for the Konza Praire case about 100% and 93% of the nighttime and daytime hours, respectively. The annual power requirement would be 336,000 kW-hr, which at a power price of $0.1/kW-hr means the annual operating cost would be $33,600 per 8-m-diameter plot.

I. **Introduction and NEON Requirements**

As communicated by Mr. Keith Lewin, Brookhaven National Laboratory, there is a need to warm free-air ecological field plots to determine the likely effects of global warming on various ecosystems for NEON, the National Ecological Observatory Network. In order to simulate ecological processes in a near-natural way, is desired that such plots be at least of 20-m scale, and to simulate the likely effects of global warming near the end of this century, the degree of warming in the plots needs to be controlled to be at least 4ºC above today's normal ambient temperatures. However, operating budget constraints suggest that 20-m diameter plots may be fiscally impossible, so smaller plot scales are also considered. Section II presents calculations for 20-m plots and Section III for 8-m diameter plots.

We have previously achieved warming of open-field plots using a T-FACE (temperature free-air controlled enhancement) system on grazing land (Kimball *et al.*, 2008) and currently on wheat here at the U.S. Arid-Land Agricultural Research Center. Our current T-FACE system uses six 1000W infrared heaters deployed in a hexagonal pattern over 3-m-diameter (7.1 m^2) plots to warm the plant canopies by 1.5ºC during daytime and 3.0ºC at night. For a short time, we also tested the system over a 5-m-diameter plot, which is a near-tripling of the area (19.6 m^2) (Kimball and Conley, 2009). For this test we deployed eighteen of the 1000W heaters in a similar hexagonal pattern. For both the 3- and 5-m-diameter plots, excellent uniformity of the warming was achieved when the heaters were at a height of 0.4*diameter and were tilted at 45º from vertical and pointed toward the center of the plot. Moreover, the same equation was applicable for both plot sizes to calculate the efficiency (amount of downwelling thermal radiation from the heaters within the plot area per amount electrical energy input) from wind speed [efficiency (%) = $10 + 25e^{(-0.17u)}$, where u is wind speed at 2-m height ($m\ s^{-1}$)].

However, the NEON requirements represent a substantial increase in scale. A 20-m-diameter (314 m^2) plot has 44 times the area of a 3-m-diameter (7.1 m^2) plot, and an 8-m plot (50.3 m^2) has 7.1 times as much. Also, 4ºC of warming is 2.67 times as much warming as the 1.5ºC we have been doing during daytime (when atmospheric turbulence is highest and when plant stomata are open so transpiration is generally occurring). In our experience under our Maricopa conditions, the $6000W/7.1m^2 = 845\ W/m^2$ of heater power is just marginal for achieving the desired 1.5ºC of daytime warming. Therefore, to achieve 4.0ºC of warming (under similar conditions and with heaters of similar efficiency), about 2300 W/m^2 will be required, which amounts to about 708 kW for a 314 m^2 plot or 116 kW for a 50.3 m^2 plot.

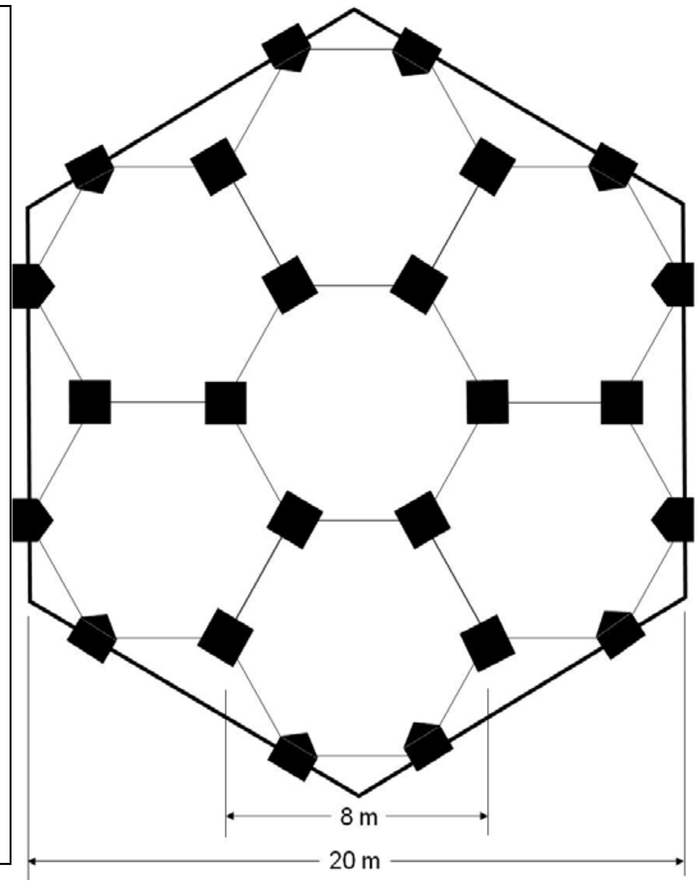
I. Scaling to 20-m-Diameter Plots

Heater Selection and Deployment

An infrared heater power requirement of 708 kW is huge in comparison to the size of commercially available infrared heaters, especially those whose thermal radiant properties are suitable for this plant-warming application (Kimball, 2005). Also, most commercially available heaters are only suitable for indoor use, and much effort would be required to water-proof them and make them safe and reliable for outdoor use. The Mor-FTE-1000 heaters[2] we have used previously (Kimball *et al.*, 2008; Kimball and Conley, 2009) could be used, but about 700 of them would be required, and even then considerable labor and high-temperature sealant is needed to make them safe for outdoor usage.

One candidate heater that might be used is a Raymax 1010 manufactured by Watlow Electrical Manufacturing Company (http://www.watlow.com/literature/specsheets/files/heaters/stl10100805.pdf), which is available in a totally liquid-tight model. The emitting surface is stated to have an emissivity very close to that of a black-body, and with an emittance of $10 W/in^2$ ($15.5 kW/m^2$), it should have excellent thermal radiant properties with almost no emission of energy at wavelengths that would be plant morphogenically active. The heaters are custom made to customer-specified sizes, but the largest they manufacture apparently is 8600W, 18 inches wide by 48 inches long (.457 m by 1.219 m = $0.557 m^2$). Thus, to achieve 708 kW, 82 such heaters would be required.

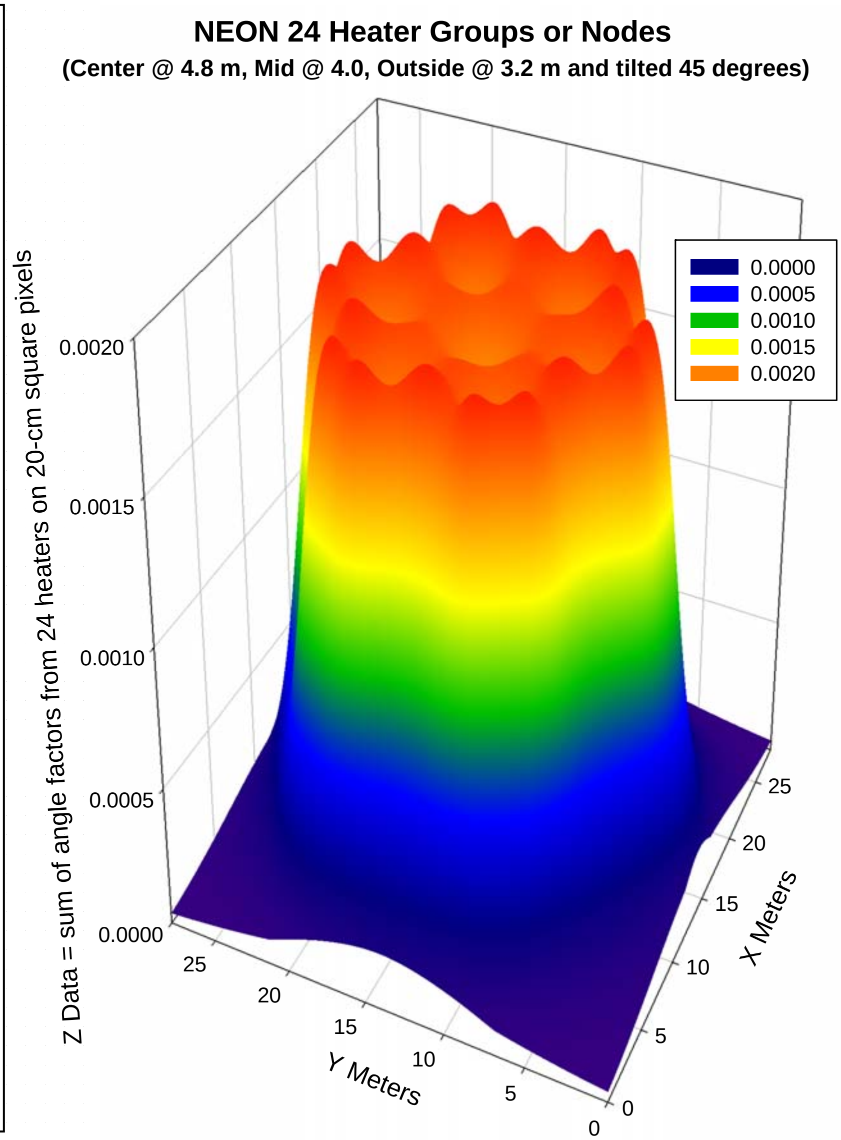
Figure 1. Schematic diagram for the deployment of infrared heaters over a 20-m-diameter hexagonal plot via the use of seven internal 8-m-diameter hexagons. Three (or possibly four) heaters would be deployed at each of the 24 nodes where lines connect. The heaters at each of the 12 outer nodes would be tilted at 45° from vertical and pointed in the indicated direction, i.e. toward the center of the smaller internal hexagon, whereas the heaters at the internal nodes point nadir. The size of the square and arrow symbols at the nodes approximates the area of the heaters when viewed from nadir.



[2] 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 U.S. Department of Agriculture.

How should so many heaters be deployed over the plot to achieve adequate uniformity, high energy efficiency, and little solar shading? Compromises will be required to achieve all three objectives satisfactorily. One possibility would be to deploy six groups of 14 heaters each in a Another scheme for deploying the heaters would be to erect seven smaller (8-m-diameter) arrays

Figure 2. Theoretical distribution of the thermal radiation received on a plot surface from 24 groups (or nodes) of black-body flat plate heaters deployed in the hexagonal patterns depicted in Fig. 1. The six center heater groups are at a height above the vegetation canopy of 4.8 m and they point nadir. Likewise, the six heater groups at a mid position between center and outside point nadir, and they are at a height of 4.0 m. The twelve heater groups around the periphery are at a height of 3.2 m, tilted at 45° from vertical, and pointed toward the center of the smaller hexagons. The vertical axis is the sum of angle factors from each of the 24 nodes to 20-cm pixels on the plot surface.



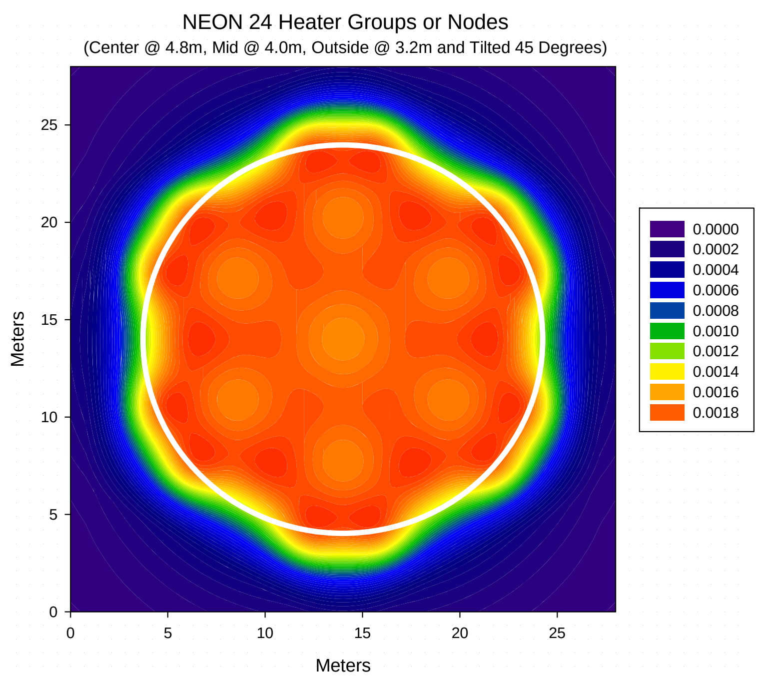
within the overall 20-m-diameter array, as suggested by Keith Lewin (Fig. 1). Many texts on the topic of heat transfer present theory on the exchange of thermal radiation between uniform black body surfaces (e.g., Gebhart, 1961; http://www.me.utexas.edu/~howell/). They show that the radiant emission, $q_{1\text{-}2}$ (W) from surface A_1 which goes directly to A_2 is $q_{1\text{-}2} = F_{12}W_1A_1$, where W_1 is the emissive power (W m^{-2}) of surface 1, A_1 is its area (m^2), and F_{12} is an angle or view factor that is dimensionless and depends solely on the geometrical orientation of the two surfaces with respect to each other. They show that in general the angle factor from an elemental area of surface 1 to an elemental area of surface two is $dF_{d1\text{-}d2} = (\cos \Theta_1 \cos \Theta_2)(\pi S^2)^{-1}dA_2$ where S is the length of the line from the surface 1 element to the surface 2 element, Θ_1 is the angle between S and the normal to surface 1, Θ_2 is the angle between S and the normal to surface 2, and dA_2 is the area of

the element of surface 2 (e.g., Gebhart, 1961; http://www.me.utexas.edu/~howell/). By deriving equations to express S, cos Θ_1, and cos Θ_2, in terms of the distances from 20-cm-square pixels on the plot surface to heater surfaces at each of the nodes and then summing up the angle factors for all 24 nodes, I was able to calculate the theoretical distribution of thermal radiant energy from the array of heaters depicted in Fig. 1 over the whole 20-m plot, as well as areas outside the plot (Figs. 2 and 3).
hexagonal pattern around the periphery in an extension of the approach used by Kimball and Conley (2009). The heaters would be deployed at a height of 0.4*20-m diameter = 8 m above the vegetative canopy, tilted at 45° from vertical, and pointed toward the center of the plot. If deployed horizontally over the plot, the total area of 84 of the Watlow heaters would be 46.8 m^2, so solar shading would be about 15%. However, when tilted at 45°, and assuming only half would be shading because they're at the periphery, the solar shading would closer to 5%. About half the perimeter would have a heater above it.

After calculating the distribution of thermal radiation for several test heights of the heaters, the configuration depicted in Figs. 1 and 2 was selected because it provides excellent uniformity. For this configuration, the six center heater groups are at a height of 4.8 m pointing nadir, the six mid heater groups are at a height of 4.0 m pointing nadir, and twelve outer heater groups are at a height of 3.2 m pointing toward the center of the small hexagons with a tilt of 45°. The coefficient of variation within the plot area is only 5.4%, which confirms that the uniformity of the theoretical distribution of the thermal radiation is excellent across the 20-m-diameter plot.

However, while the uniformity of the 24-node array in Figs. 1, 2, and 3 is excellent, solar shading is worse than that of the single hexagon used previously (Kimball *et al.*, 2008; Kimball and Conley, 2009). Deploying the center and mid heater groups horizontally and the outer groups at an angle of 45° and assuming that only half of the outer groups do shading, the overall solar shading for 72 heaters (3 per node) would be about 8%.

Figure 3. Two-dimensional color contour depiction of the theoretical distribution of the thermal radiation received on a plot surface from 24 groups (or nodes) of black-body flat plate heaters deployed in the hexagonal patterns depicted in Fig. 1. The color code and the heights and orientations of the 24 heater groups are the same as in Fig. 2. The white circle has a diameter of 20 m and indicates the border of the useable plot area.



Infrared Heater Efficiency

The efficiency of an infrared heater array is the amount of useful thermal radiant energy that falls within the plot area per amount of electrical energy input. Thus, the overall efficiency has two components: one accounts for the losses due to convection of energy away from the hot heater element by the wind or buoyancy (i.e., "convective efficiency"), and the other accounts for the losses due to thermal radiant energy falling outside the plot area (i.e. "geometric efficiency"). If an infrared heater is very close to the surface being warmed, then the geometric efficiency would approach 100%, whereas if a heater is raised to ever higher elevations above a plot, more and more radiation will fall outside the plot area, thereby lowering geometric efficiency. Furthermore, when the heaters are tilted away from nadir, more radiation can escape to the sky and potentially other areas outside the plot in the direction the heater is pointed, while in the back direction, less radiation will escape the useable area. Manufacturers of many models of infrared heaters add reflectors of various designs to try to reflect some of the thermal radiation that otherwise would be lost back toward the intended useable area and thereby improve geometric efficiency. The angle factor calculations for planer black bodies in the previous section do not include reflectors, so therefore, they are "worst cases," and opportunities may exist for improvements by adding reflectors. However, improvements in geometric efficiency with reflectors likely come at the cost of greater solar shading.

Table 1. Dimensions and other characteristics of various infrared heaters.

Manufact.[1]	**Model**	**Power**	**Shape**	**Length**	**Width**	**d**[2]	**Radiating Surface Material**	**Emis.**
		(W)		(mm)	(mm)	(mm)		
Kalglo	HS-2420	2000	rod	1510	8	8	incoloy	0.44[3]
Mor	ESES	250	disk	105	105	105	glaze[4]	0.96[5]
Mor	FTE	1000	rectangle	245	60	60	glaze[4]	0.96[5]
Watlow	Raymax[6]	8600	rectangle	1219	457	457	black paint	0.96[5]
Watlow	Raymax[6]	25800[7]	rectangle	1371[7]	1219[7]	1219[7]	black paint	0.96[5]

[1]Manufacturers' names are listed for the benefit of the reader and do not imply any special endorsement by the U.S. Department of Agriculture.
[2]d = characteristic dimension, which is the diameter of cylinders and disks or the shortest side of a rectangle for use in convection equations from Campbell (1977).
[3]Emissivity from Kimball (2005).
[4]Ceramic coated with glaze.
[5]Emissivity from manufacturers' claims.
[6]Specifically liquid-tight Raymax 1010.
[7]Bank of three of the Watlow 457 mm by 1219 mm infrared heaters adjacent to each other.

Based on the angle factor calculations described in the previous section, the theoretical “geometric efficiency” of the seven-hexagon configuration (Figs. 1, 2, and 3) should be about 58%. While 58% seems rather low, nevertheless it is considerably higher than the corresponding value of 37% calculated for a single hexagon with all the heaters tilted at 45° around the periphery (Kimball *et al.*, 2008; Kimball and Conley, 2009).

Kimball (2005) presented theory to predict the convective efficiency of infrared heaters based on convective heat transfer equations from Campbell (1977). The equations are based on prior work using flat plates in laminar flow, so real heaters in the more turbulent outdoors may have higher convective heat transfer coefficients and consequently somewhat lower efficiencies than the theoretical values. Nevertheless, the theory is useful for predicting approximate performance.

Huge differences in theoretical convective efficiency exist among various designs of infrared heaters (Fig. 4). Because of the small characteristic dimension of the rod-shaped Kalglo heater and its low emissivity, its theoretical convective efficiency is the lowest among the several heaters examined. On the other hand, it has a large effective reflector housing, so that it is geometrically efficient, yet the resultant overall efficiency is still quite low as indicated by measurements [turquoise line in Fig. 4 from Kimball (2005)]. Looking at the theoretical curves for the other heaters in Fig. 4, it is apparent that increasing emissivity and increasing the characteristic dimension greatly improves the efficiency. A comparatively large 1.2 x 1.8 m heater from Watlow (actually 4 adjacent 1.2 x 0.46 m heaters) oriented nadir would have convective efficiencies ranging from about 93 to 69% for wind speeds from 0 to 14 m s^{-1}.

However, the theoretical convective efficiencies in Fig. 4 do not account for thermal radiation that falls outside the plot area, i.e. the geometric efficiencies. The geometric efficiencies for single hexagonal arrays of Mor-FTE infrared heaters (Kimball *et al.*, 2008) and of 24-node coupled hexagonal arrays (Fig. 1) are plotted as lines in Fig. 5. Also shown in Fig. 5 are the overall (geometric times convective) efficiencies of the two types of arrays. The theoretical overall efficiency of the single hexagonal array of Mor-FTE heaters is close to that of measured curve for 3-m-diameter plots (Kimball *et al.*, 2008), as well as 5-m plots (Kimball and Conley, 2009). This agreement with measured data gives confidence for using the theoretical curves.

The overall efficiency of a 20-m-dimater, 24-node connected infrared heater array of large Watlow heaters (Fig. 1) ought to be considerably higher than the overall efficiency of a single 3-m-diameter hexagonal array (Fig. 5). At zero wind, the efficiency increase should be from about 32 to 47% and at a high wind of 14 m s^{-1}, the increase should be from about 18 to 32%. Such an increase in efficiency implies that 3 heaters per node should be sufficient rather than four for a total of 72 heaters rather than 96.

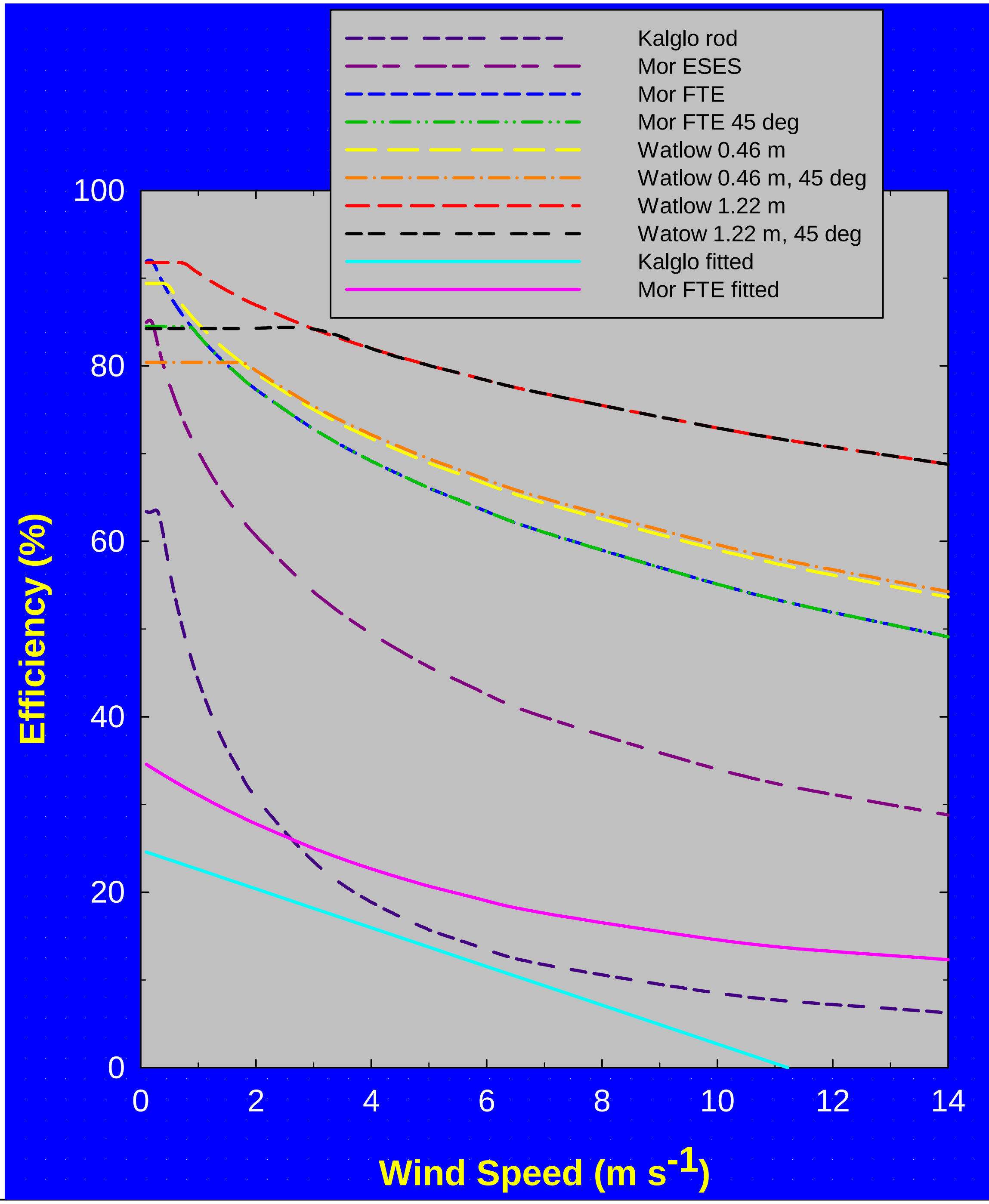


Figure 4. Theoretical convective efficiencies of several infrared heaters calculated using the theory derived by Kimball (2005). The characteristics of the heaters are listed in Table 1. The theory is based on flat plate equations from Campbell (1977) for air at 20°C and 100 kPa pressure. For heaters tilted at 45°, the coefficient for free-convection at low wind speed was assumed to be the same as that of a heated plate facing upward, whereas for heaters pointed down, the coefficient was one half that of an upward facing plate. The Kalglo fitted line is the measured overall efficiency of a Kalglo infrared heater (Kimball, 2005), and similarly the Mor-FTE fitted curve is the measured overall efficiency of a hexagonal array of Mor-FTE infrared heaters deployed over a 3-m-diameter plot (Kimball *et al.*, 2008).

Thermal Radiation and Electrical Power Requirements

Kimball (2005) derived an equation that predicts the amount of additional thermal radiation required to warm a plant canopy as a function of microclimatic and plant parameters, and in the previous section, the efficiencies of infrared heater systems were addressed. From the radiation requirement and the efficiency, the amount of electrical power per m^2 of ground area and degrees of warming can be calculated. However, plant canopies vary immensely in their architecture, and their stomatal conductance changes drastically from night to day and, at least for temperate climates, from summer to winter. Further, the microclimatic variables, among which wind speed is especially important, are continually changing from night to day and from one weather pattern to another. Therefore, the cost of an infrared warming treatment in a proposed NEON experiment will depend greatly on site selection and the vagaries of weather.

Nevertheless, some assumptions can be made from which estimates of electrical power can be calculated. First, the Konza Prairie has been mentioned as at least one site for NEON. Therefore, the following assumptions were made: (1) The architecture and stomatal characteristics are similar to those of 0.5-m-tall alfalfa for which standardized equations exist for predicting evapotranspiration (Allen *et al.*, 2005), and (2) that the vegetation is actively growing and non-water-stressed during the months from April through October and is dormant from November through March. Then, using hourly weather data for 2007 that was downloaded from the Konza Prairie Web site (http://www.konza.ksu.edu/data_catalog/meteoro/) along with the overall efficiency curve for a 24-Node array (Figs. 1 and 5), following Kimball (2005; Eq. 14) and Kimball *et al.* (2008), infrared heater electrical power requirements were computed (Fig. 6).

The most striking feature of the frequency curves of the heater power requirements (Fig. 6) is the large spike for the night, 24-node efficiency curve at about 50 W m^{-2} C^{-1}. However, this is probably not real but rather is likely an artifact of the researchers assigning a constant 0.41 m s^{-1} wind speed under calm conditions when their anemometers stalled. Nevertheless, the cumulative fractions are most useful for this analysis and this spike (as well as one night, 6-node efficiency) at very low wind speeds do not affect the annual power requirement estimates. As expected from the general tendency for there to be more turbulence and higher wind speeds during daytime, the frequency curves for daytime have broader peaks and extend to much higher power requirement values compared to nighttime. Most importantly, the higher efficiency of the 24-node array led to a large shift of the curves to lower power requirements compared to the curves for the 6-node efficiency.

The cumulative fraction curves (Fig. 6) are most useful for estimating the percentage of the time that various heater combinations can meet the desired 4˚C warming target. The vertical dotted line at 493 W m^{-2} C^{-1} in Fig. 6 corresponds to the unit heater capacity for 72 8600-Watt Watlow infrared heaters deployed over the 314 m^2 plot with 4˚C of warming. The horizontal dotted lines indicate where the 493 line crosses the daytime cumulative fraction curves for 6-node and 24-node efficiencies, respectively. Following these horizontal lines to the right axis, the cumulative fractions of the daylight hours that this 72-heater array can meet the 4˚C target are 0.57 and 0.94 for the 6-node and 24-node efficiencies, respectively. In other words, 72 of the 8600-watt Watlow heaters can meet the requirement 57% of the daylight hours if we assume that the efficiency of the array is no better than that observed previously with 3-m arrays (Kimball *et al.*, 2008). On the other hand, if we assume that the newly predicted overall efficiency for a 24-node array is correct (Fig. 5), then the same 72-heater array should be able to meet 94% of the daytime heating requirements.

Using Fig. 6, the percentages of time that arrays with 48, 72, and 96 of the 8600-watt Watlow heaters in a 24-node array (Fig. 1) can meet the 4˚C heating requirement were estimated (Table 2). If the efficiency curve for the 6-node, 3-m-dimeter is applied for this much larger 24-node, 20-m-diameter plot, it appears that 48, 72, and 96 heaters could only meet the requirements only 32, 57, and 76% of the daylight hours, respectively. On the other hand, if the 24-node efficiency curve is assumed, the heating requirement should be met 72, 94, and 99% of the daylight time. For nighttime, all the heater combinations can meet the requirements at least 78% of the time even if the 6-node efficiency is assumed.

Following the methodology described in the previous section, the total annual electrical power requirements were calculated assuming unlimited heater capacity for both the 6-node and 24-node efficiency assumptions (Table 2). However, for some of the time, especially under windy conditions, the heaters will be fully on and yet unable to meet the heating requirements, so the actual power consumed will be only that of the heater capacity. Therefore, the power requirements were calculated for the heater capacities corresponding to 48, 72, and 96 of the 8600-W Watlow heaters (Table 2). As expected, the power requirements go down with deceasing number of heaters. However, the most dramatic differences are between the efficiency assumptions.

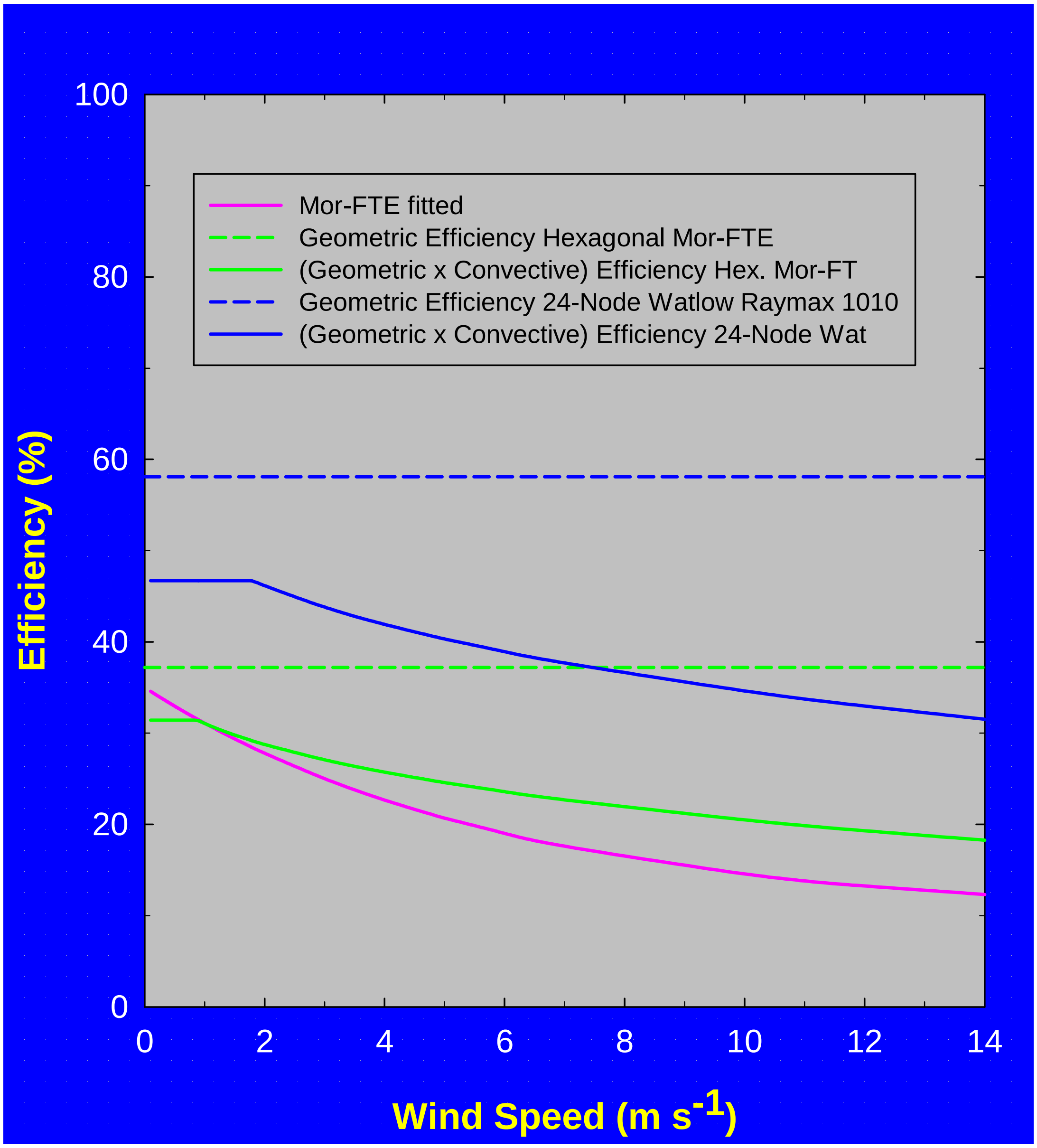


Figure 5. Geometric efficiencies of single hexagonal arrays of Mor-FTE infrared heaters and of 24-node connected hexagonal arrays shown in Fig. 1. Also shown are the total (geometric times convective) efficiencies for the two types of arrays. For the 24 node array, the Watlow heaters were assumed to have convective efficiencies of the 0.46-m width, 45-degree tilt Watlow heaters in Fig. 4. The Mor-FTE fitted curve is the measured overall efficiency of hexagonal arrays of Mor-FTE infrared heaters deployed over 3-m-diameter plots (Kimball *et al.*, 2008).

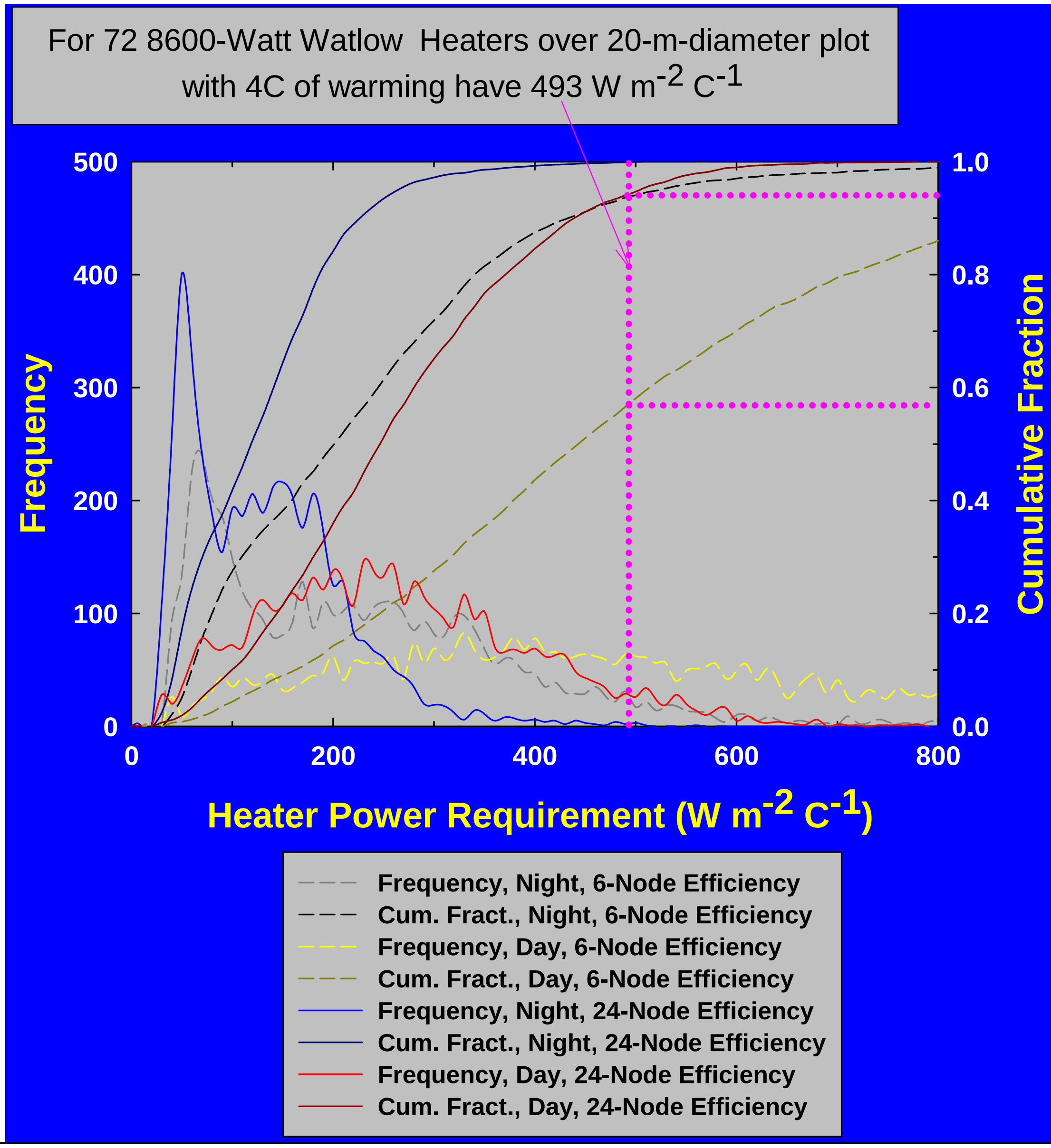


Figure 6. Frequency and cumulative fractions of hourly electrical power requirements for 24-node infrared heating of a 20-m-diameter open-field plot (Fig. 1) using 2007 weather data from Konza Prairie, KS, for separate night and daytime conditions. Two efficiency equations were used: (1) the equation from Kimball *et al.* (2008) for a 6-node, 3-m-diameter single hexagonal array with the heaters around the periphery and (2) the overall equation from Fig. 5 for a 24-node, 20-m-diameter 7-hexagon array (Fig. 1). The vegetation properties were those of 50-cm-tall alfalfa (Allen *et al.*, 2005) assuming no water stress (i.e., maximum evapotranspiration) during the months of April through October and dormancy from November through March. The dotted lines indicate that 72 8600W Watlow heaters deployed over the 20-m plot with 4C of warming amounts to 493 W m^{-2} C^{-1}, which means that the array should meet the daytime heating requirement about 94% of the daylight hours if the efficiency equation from Fig. 5 is correct or only about 58% of the daytime hours if the array were only as efficient as that of Kimball *et al.* (2008).

Table 2. Percentages of time that target degrees of warming (4°C) can be met for 24-node, seven-hexagon infrared heater arrays with deployment of 48, 72, or 96 8600-W Watlow heaters assuming that the efficiency of the array is the same as that determined by Kimball *et al.* (2008) for single hexagonal arrays (6-node) or is that predicted by the overall efficiency curve from Fig. 5 for a 24-node array. Also presented are the estimated annual electrical energy requirements and their corresponding costs. The computations were made with hourly weather data for 2007 for the Konza Prairie, KS with the 6-node and 24-node efficiencies applied to thermal energy requirements calculated following Kimball (2005, Eq. 14).

	Efficiency	
Item	**6-node**[1]	**24-node**[2]
Percentage of time target (4°C) heating can be met (%)[3]		
During daytime		
For 96 heaters	76	99
For 72 heaters	57	94
For 48 heaters	32	72
During nighttime		
For 96 heaters	98	100
For 72 heaters	94	99
For 48 heaters	78	98
Annual electrical energy requirement (kW-hr per plot)		
For unlimited heater capacity	3,920,000	2,120,000
For 96 heaters[4]	3,600,000	2,120,000
For 72 heaters[4]	3,270,000	2,110,000
For 48 heaters[4]	2,670,000	1,970,000
Annual power cost[5] ($ per plot)		
For unlimited heater capacity	392,000	212,000
For 96 heaters[4]	360,000	212,000
For 72 heaters[4]	327,000	211,000
For 48 heaters[4]	267,000	197,000
Extrapolated from prior 3-m plot experiments[6]	275,000	-

[1]Efficiency equation from Kimball *et al.* (2008) for single hexagonal array with all heaters around the periphery.

[2]Efficiency equation from overall curve for 24-node array from Fig 5.

[3]From Fig. 6 where the unit power requirement was calculated from:
(number of heaters)(8600W)$(314\ m^2)^{-1}(4°C)^{-1}$
which equals 657, 493, and 238 $W\ m^{-2}\ C^{-1}$ for 96, 72 and 48 heaters, respectively.

[4]8600 Watts each.

[5]At 0.1$ per kW-hr.

[6]Assumed (1) that the efficiency of the 20-m-array will be that of the 3-m-arrays, (2) that the power usage will be about 11.5 kW-hr/day/m^2 (Table 3) x (4.0/1.5) for 4°C of warming x 314 m^2 = 9629 kW-hr/day per 20-m-diamber plot for actively growing vegetation, (3) that half as much is needed when the vegetation is dormant, and (4) that the vegetation is active for 7 months per year and dormant 5 months per year.

Electrical Power Operating Costs

Electrical power prices vary region by region and even by time of day, but often are close to \$0.1 per kW-hr. Under this price assumption, the annual electrical energy requirement values (Table 2) were multiplied by 0.1 to estimate annual power costs (Table 2). Assuming the 6-node efficiency, annual power costs likely will be on the order of \$267,000, 327,000, or \$360,000 per 20-m plot for 48, 72, and 96 heater arrays, respectively.

The energy requirement values in Table 2 were calculated using Konza Prairie weather and vegetation characteristics of alfalfa, and so the question arises as how accurate they can be. While no one has yet constructed an infrared heater array like that in Fig. 1, several groups have gained experience with smaller 3-m-diameter arrays. Table 3 lists observations of energy use from three such sites where infrared heater array experiments are underway. If we assume (1) that the efficiency of the 20-m-array conservatively will be no higher than that of the 3-m-arrays, (2) that the power usage will be about 11.5 kW-hr/day/m^2 (Table 3) x (4.0/1.5) for 4°C of warming x 314 m^2 = 9629 kW-hr/day per 20-m-diamber plot for actively growing vegetation, (3) that half as much is needed when the vegetation is dormant, and (4) that the vegetation is active for 7 months per year and dormant 5 months per year, then the annual power usage would be about 2,750,000 kW-hr per heated plot. At an electrical power price of \$0.1/kW-hr, therefore, the annual operating cost for electricity would be on the order of \$275,000 per heated 20-m-diameter plot (last line of Table 2). Thus, an extrapolation of the observed power use from these other systems is consistent with the totally theoretical calculations under the assumption that the efficiency is no better than that of the 6-node, 3-m arrays.

However, based on the analyses in previous sections, we have reason to believe that the geometric efficiency will be higher with the larger plot size and that the convective efficiency will be higher with larger characteristic dimensions of the heaters themselves. Therefore, assuming the 20-m, 24-node efficiency is more correct, the annual power costs are likely to be about \$197,000, \$211,000, and \$212,000 for 48, 72, and 96 heater arrays.

I am cautiously optimistic that the 24-node efficiency curve from Fig. 5 is close to correct. Therefore, the 24-node design (Fig. 1) with 72 of the 8600-W Watlow heaters combination appears most promising.

Table 3. Energy consumption and power costs for 3-m-diameter hexagonal arrays of Mor-FTE 1000W infrared heaters over grazing land at Haibei, China and Cheyenne, WY and over wheat at Maricopa, AZ. The power price is estimated to be $0.1/kW-hr. The Maricopa data include an air conditioned trailer and an irrigation pump, and they are based on times when the wheat was actively growing.

Item	**Haibei** (1.2/1.7°C)	**Cheyenne** (1.5/3.0°C)	**Maricopa** (1.5/3.0°C)
kW-hr/day/m^2	8.2	11.3	11.8
kW-hr/day/plot	58	80	84
kW-hr/yr/plot	21,000	29,000	31,000
$/yr/plot	$2,100	$2,900	$3,100

Initial Capital Costs

In order to determine the initial capital investment, a determination must be made with regard to what structure would be required to deploy the heaters as depicted in Figs. 1, 2, and 3. More engineering is desirable, but one possibility is the use of 2" (50 mm) posts with 1½" (38 mm) cross members held together with Kee Klamps (e.g., http://www.simplifiedbuilding.com/products/1-kee-klamp.html) as indicated in Fig. 7.

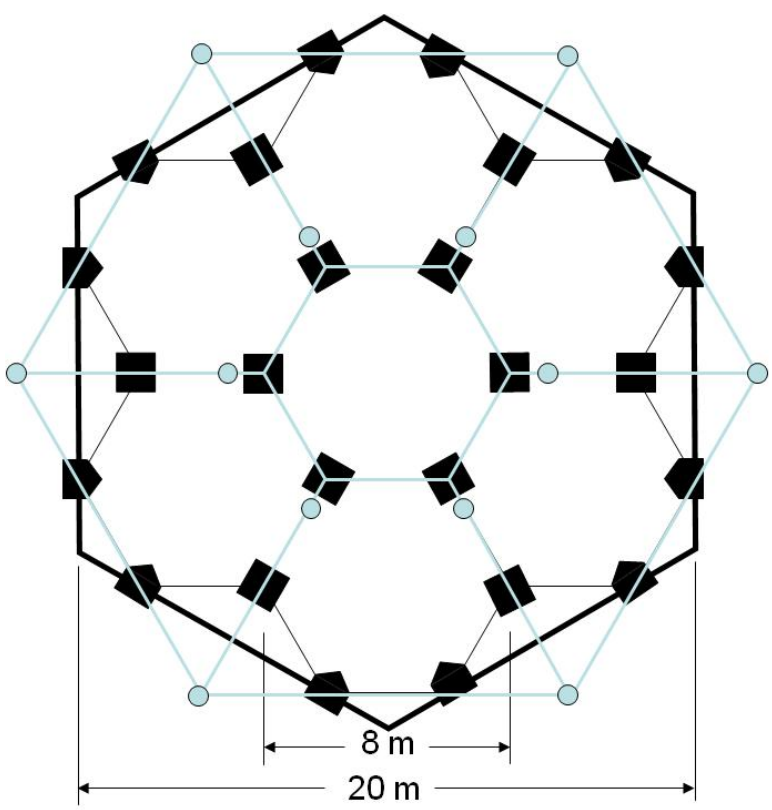


Figure 7. Schematic diagram of structure to deploy the infrared heaters shown in Fig. 1. The circles are vertical posts from 2" (50 mm) pipe. The cross members are 1½" pipe (38 mm) all held together by Kee Klamps. The outer pipes are at an elevation to deploy the outer heaters at an average 3.2 m height above the vegetative canopy and tilted 45°. The pipes that go from outside to inside are angled at 45° so as to deploy the mid heaters at 4.0 m and the center heaters at 4.8 m. The inner hexagon of pipes is needed to tie the structure together and provide strength.

We previously noted that such a 24-node array (Fig. 7) with 72 heaters should have adequate capacity to warm the plot to the target 4˚C most of the time (Table 2). Here we also note that 72 heaters per 24 nodes means 3 heaters per node, which is advantageous for 3-phase wiring.

The construction cost for a 20-m-diameter infrared heater array with 72 Watlow liquid-tight infrared heaters plus that for a corresponding reference plot is likely to be about $180,000 (Table 4). However, the uncertainties surrounding the costs for the electrical load center and associated connectors and cabling are high.

Table 4. Estimated construction cost for 20-m-diameter plot warmed with 72 8600-W Watlow liquid-tight infrared-heaters plus that for corresponding reference plot with dummy heaters.

E:\Experiments\IR Heater\NEON\[NEON Parts list 20 m dia 24 nodes 72 heaters V2.xls]Detailed						
Parts and Equipment list for 20-m hexagonal infrared heated plot						
plus similar reference plot with dummy heaters						
Has 24 nodes defining 7 interior 8-m hexagons.						
Heaters at inner 6 nodes are at 4.8-m height and pointed nadir.						
Heaters at mid 6 nodes are at 4.0-m height and pointed nadir.						
Heaters around outside are at 3.2-m height and pointed 45 deg from horizonatal toward center of their respective inner hexagon.						
Has 72 8600W, 480V Watlow Liquid-tight heaters. Total of 620 kW, 480V, 1300 amps						
Item	**Approx. Cost Each US$**	**No. per plot**	**Cost per plot US$**	**No. plots**	**Total No. needed**	**Total cost $US**
For heated plot						
Flat Radient Panel Liquid-Tight 8600W 480V Heaters [Watlow Raymax 1010 (18"x48")]	1400	72	$100,800	1	72	$100,800
Mounting hardware	100	72	$7,200	1	72	$7,200
Dimmers (Watlow)	15000	1	$15,000	1	1	$15,000
Enclosure for dimmers, circuit breakers, etc	2000	1	$2,000	1	1	$2,000
Load Center	10000	1	$10,000	1	1	$10,000
Cabling and connectors	10000	1	$10,000	1	1	$10,000
Posts (2" pipe - 20 ft sections)	40	12	$480	1	12	$480
Kee Klamps at outer posts (3 at each post, 2" x 11/2" Tees)	22	18	$396	1	18	$396
Kee Klamps at outer posts (1 at each post, 11/2" swivel Tees)	19	6	$114	1	6	$114
Kee Klamps at middle posts (1 at each post, 2 x 11/2" Tees)	22	6	$132	1	6	$132
Kee Klamps at middle posts (1 at each post, 11/2" swivel Tees)	19	6	$114	1	6	$114
Pipe from outer post to past inner posts (26 ft 11/2")	40	6	$240	1	6	$240
Pipe from outer post to outer post (40 ft 11/2")	60	6	$360	1	6	$360
Pipe from inner post to inner posts (13 ft 11/2")	20	6	$120	1	6	$120
Kee Klamps if needed to couple to make 40 ft (11/2 couplings)	13	6	$78	1	6	$78
Kee Klamps at center joints (11/2" tee)	12	12	$144	1	12	$144
Kee Klamps at center joints (11/2" swivel tee)	19	12	$228	1	12	$228
Infrared thermometer (Apogee IRR-PN; four per 20-m plot)	600	4	$2,400	1	4	$2,400
PVC housing for IRT (home-made)	20	2	$40	1	2	$40
4 conductor cable	0.2	120	$24	1	120	$24
		Subtotal =	**$149,870**			**$149,870**
For reference plot						
Dummy Heaters (use sheet metal)	200	72	$14,400	1	72	$14,400
Mounting hardware	100	72	$7,200	1	72	$7,200
Posts (2" pipe - 20 ft sections)	40	12	$480	1	12	$480
Kee Klamps at outer posts (3 at each post, 2" x 11/2" Tees)	22	18	$396	1	18	$396
Kee Klamps at outer posts (1 at each post, 11/2" swivel Tees)	19	6	$114	1	6	$114
Kee Klamps at middle posts (1 at each post, 2 x 11/2" Tees)	22	6	$132	1	6	$132
Kee Klamps at middle posts (1 at each post, 11/2" swivel Tees)	19	6	$114	1	6	$114
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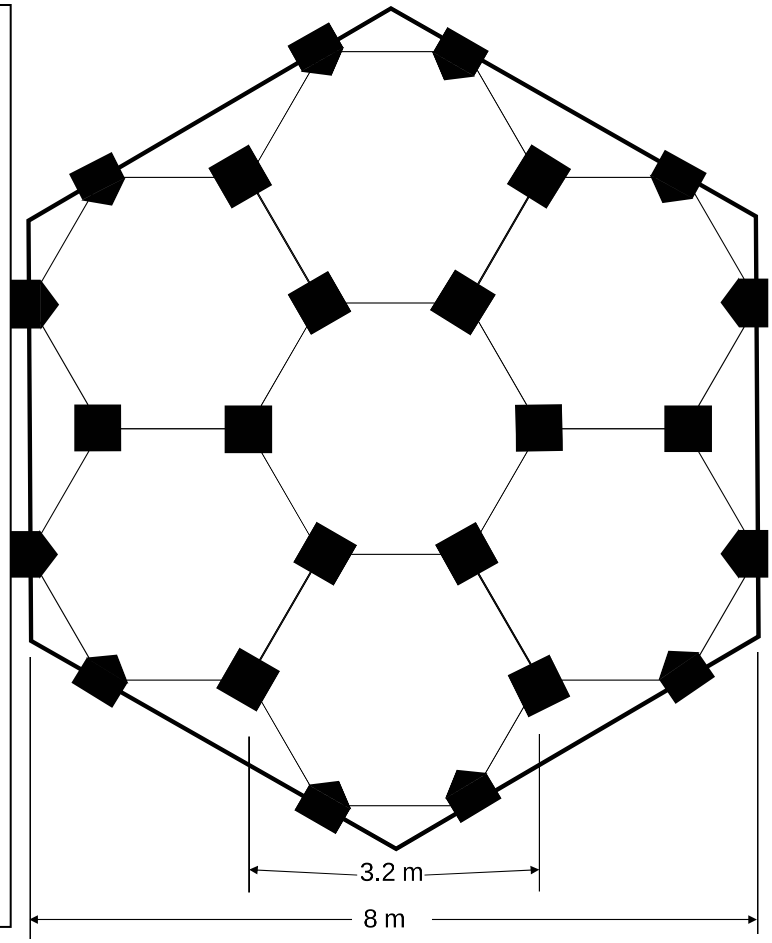
Pipe from outer post to outer post (40 ft 11/2")	60	6	$360	1	6	$360
Pipe from inner post to inner posts (13 ft 11/2")	20	6	$120	1	6	$120
Kee Klamps if needed to couple to make 40 ft (11/2 couplings)	13	6	$78	1	6	$78
Kee Klamps at center joints (11/2" tee)	12	12	$144	1	12	$144
Kee Klamps at center joints (11/2" swivel tee)	19	12	$228	1	12	$228
Infrared thermometer (Apogee IRR-PN; four per 20-m plot)	600	4	$2,400	1	4	$2,400
PVC housing for IRT (home-made)	20	1	$20	1	1	$20
		Subtotal =	**$26,426**			**$26,426**
For whole experiment						
Black body calibrator (Everest Interscience 1000?)	930	1	$930	1	1	$930
Portable handheld infrared thermometer? (Everest Interscience 100.3ZL?)	3040	1	$3,040	1	1	$3,040
		Subtotal =	**$3,970**			**$3,970**
		Total =	**$180,266**			**$180,266**

III. Scaling to 8-m Diameter Plots

As noted in the previous section, the 24-node, 7-hexagon infrared heater distribution pattern depicted in Fig. 1 has several advantages, including excellent distribution of the thermal radiation across the plot (Figs. 2 and 3), relatively high efficiency (Fig. 5), and acceptable solar shading (about 8%). Therefore, an obvious approach is to explore scaling the array in Fig.1 down to 8-m, as shown in Fig. 8. Because the geometry in Fig. 8 is all scaled down proportionally from that in Fig. 1, the angle factors are all the same, and therefore the distribution pattern of the thermal radiation will also be the same [Figs. 5 and 6 with the meter axes scaled by (8 m/20 m)]. Likewise, the theoretical geometric efficiency will be the same, 58%.

Figure 8. Schematic diagram for the deployment of infrared heaters over a 8-m-diameter hexagonal plot via the use of seven internal 3.2-m-diameter hexagons. A heater would be deployed at each of the 24 nodes where lines connect. The heaters at each of the 12 outer nodes would be tilted at 45° from vertical and pointed in the indicated direction, i.e. toward the center of the smaller internal hexagon, whereas the heaters at the internal nodes point nadir. The size of the square and arrow symbols at the nodes approximates the area of the heaters when viewed from nadir. The six center heaters are at a height above the vegetation canopy of 1.92 m, the six heaters at mid-position between center and outside are at a height of 1.6 m, and the twelve heaters around the periphery are at a height of 1.28 m above the top of the vegetation.



Cumulative fractions of hourly electrical power requirements in Fig. 6 were computed with Konza Prairie weather data using the combined geometric and convective efficiencies for Watlow infrared heaters with a characteristic dimension of 0.46 m. Starting with a cumulative fraction of 0.9 (meaning 90% of the time the heating requirement is met) on the right axis, tracing left to the curve for daytime, 24-node, the heater power requirement on the bottom axis is 440 W m^{-2} C^{-1}. Therefore, for 4˚C of warming over 50.3 m^2 of plot area, 88,500 W of heater power will be required. In section II for the 20-m plot, the candidate heater was a 8600 W Raymax 1010 from Watlow, which is the largest known that is available in a liquid-tight housing suitable for outdoor use and whose spectrum of radiant emissions is acceptable for plant growth research. Dividing 88,500 by 8600 shows that 10 such heaters would have the needed capacity. However, we have 24 nodes, so smaller heaters can be used. According to Watlow, their Raymax 1010 heaters are available in custom dimensions that vary by 2 inch increments, and they all have a maximum watt density of 10 W/in^2. The 8600 W unit is 18 inches by 48 inches (0.46 x 1.22 m). Keeping the width at 18 inches and shortening to 22 inches (0.46 m x 0.56 m) would produce at heater of 3960 W capacity, and because the smaller dimension of 0.46 m is kept the same, then the convective efficiency of these smaller heaters should be the same as that of the longer heaters used in the computations for Fig. 6. Using a heater capacity of 3960 W for 4˚C of warming over 50.3 m^2 of plot area produces a unit electrical power capacity of 473 $W\ m^{-2}\ C^{-1}$. Tracing up from 473 on the horizontal axis in Fig. 6 to the 24-node cumulative fraction curves and then to the right axis shows that such heaters ought to meet the warming requirements 100% and 93% of the nighttime and daytime hours, respectively.

Summing hour by hour through the year for the Konza Prairie example, the annual electrical power requirements for an 8-m-diameter plot will be about 340,530 kW-hr. If the heater capacity is that of the 3960W heaters introduced in the previous paragraph which will not meet the power requirement about 7% of the daylight hours, then the annual power consumption will be about 336,000 kW-hr. Therefore, at a power cost of $0.1 per kW-hr, the annual electrical operating cost for such an 8-m plot will be about $33,600 per year. And if there are 10 such heated plots, the cost will be about $336,000 per year.

The characteristics of such a 24-node infrared heater array for a 8-m-diameter field plot on the Konza Prairie are tabulated in Table 5.

Table 5. Characteristics of a 24-node infrared heater array for an 8-m-diameter field plot in the Konza Prairie, KS. There would be one flat panel heater (0.46 m x 0.56 m; 3960 W) at each node deployed as indicated in Fig. 8.

Item	**Value**
Area (m^2)	50.3
Solar shading[1] (%)	8.3
Geometric efficiency (%)	58
Geometric times convective efficiency at zero wind[2] (%)	47
Percentage of time that heating requirement can be met[3,4] (%)	
Daytime	93
Nighttime	100
Annual electrical power requirement[4] (kW-hr per 8-m-diameter plot)	336,000
Annual electrical power cost[4,5] ($ per 8-m-diameter plot)	33,600

[1]Based on heaters that are 0.46 m by 0.56 m with the twelve inner heaters pointing nadir and the twelve heaters on the periphery tilted 45° with only half providing shade at any particular time.

[2]Efficiency equation from overall curve for 24-node array from Fig 5.

[3]From Fig. 6 where the unit power requirement was calculated from:

$(24 \text{ heaters})(3960 \text{ W})(50.3 \text{ m}^2)^{-1}(4°\text{C})^{-1} = 472 \text{ W m}^{-2} \text{ C}^{-1}$.

[4]The computations were made with hourly weather data for 2007 for the Konza Prairie, KS with the 24-node efficiencies applied to thermal energy requirements calculated following Kimball (2005, Eq. 14). The vegetation was assumed to be actively growing (i.e. non-water stressed with maximum transpiration) from April through October and dormant during the other winter months.

[5]At $0.1 per kW-hr.

References

Allen, R.G., Walter, I.A., Elliott, R.L., Howell, T.A., Itenfisu, D., Jensen, M.E., and Snyder, R.L. 2005. *The ASCE Standardized Reference Evapotranspiration Equation*. American Society of Civil Engineers, Reston, VA. 195 pp.

Campbell, G.S. 1977. *An Introduction of Environmental Biophysics*. Springer-Verlag New York, Inc., New York, NY. 159 pp.

Gebhart, B. 1961. *Heat Transfer*. McGraw-Hill Book Company, Inc. New York. 454 pp.

Kimball, B.A**.** 2005. Theory and performance of an infrared heater for ecosystem warming. *Global Change Biology* 11:2041-2056.

Kimball, B.A., M.M. Conley, S. Wang, X. Lin, C. Luo, J. Morgan, and D. Smith. 2008. Infrared heater arrays for warming ecosystem field plots. *Global Change Biology* 14:309-320.

Kimball, B.A., and M.M. Conley. 2009. Infrared heater arrays for warming field plots scaled up to five meters diameter. *Agricultural and Forest Meteorology* (in press).

Appendix 3: Watlow 8600 watt infrared heater quote.
File name: Watlow 8600 W heater quote.doc.
File date: October 3, 2008

Date: Fri, 03 Oct 2008 16:02:14 -0400
From: cta <ctarpi@earthlink.net>
To: lewin@bnl.gov
Subject: Watlow Raymax 1010 Radiant Panel Heaters
Dear Keith,

We are pleased to offer the following Watlow Radiant Panel Heaters:

Qty.=96 Raymax 1010 Radiant Panel Heater **$1,399.00 ea**. **$134,304 total**
18" X 48" Overall
480V 3 Phase 8600 Watts
Totally Welded Liquid Tight Construction
36" Leads With Insulated Ground Wire
Exiting Through Conduit Fitting
(8) Mounting Studs
TC Pocket On Hot Face
Paint Hot Face Black

Ship Date: 30 Working Days to Ship ARO
F.O.B: Factory(STLOUIS)
Payment Terms: 50% Payment With Purchase Order
50% Net 30 Days (upon credit approval)
*Please Note Terms and Conditions of Sale Below

CTA/Watlow has worked well with BNL over the years and we look forward to contributing to this exciting project with you. As mentioned to you, the association CTA/Watlow can offer Sensing and Power control and Sensing with Motion Control. CTA can offer Power Controls having enough capability for 1000Amps for about $15,000 in one big unit or (10) smaller Power Controls- your design decision. Watlow individual Thermocouples at about $25.00 each or infrared units somewhat higher. We know the market well and I personally was a Raytek Sales Manager for years. Watlow Temperature Controls are the best in the business, and CTA can bring the best people to the project for the solution of choice.
Please check your immediate needs by ordering the Raymax Panel Heaters and we can have our application meetings while waiting for the heaters.

Thank You,
Barry Critides

CTA - Critides Technical Associates
Div. of Research Projects, Inc.
8400 River Road - 1st. Floor
North Bergen, NJ 07047

Phone: (201)868-4300
Fax: (201)854-0781

WE ARE PLEASED TO SUBMIT THE ABOVE QUOTATION FOR YOUR CONSIDERATION.
Quantity variations apply to all manufactured items.
Prices will be valid for 30 days and subject to change
thereafter. CTA additional terms and conditions apply.
All shipments are F.O.B. factory unless otherwise stated.

*NO RETURNS ON MANUFACTURED & SPECIAL ORDER ITEMS.

Appendix 4: Watlow 3960 watt infrared heater quote.
File name: Watlow 3960 W heater quote.doc.
File date: December 3, 2008

Subject: Quote for 24 Radiant Panel Heaters
Date: Tue, 02 Dec 2008 16:14:43 -0500
From: cta <ctarpi@earthlink.net>

Hi Keith,

Thanks for your inquiry! We are pleased to offer the following:

Qty.=24 Raymax 1010 Radiant Panel **$1048.00ea.** **$25,152.00 total**
Liquid Tight Construction
Paint Face Black
18" X 22" Overall
240V 1 Phase 3960 Watts
TC Pocket on Face
36" Power Leads Exiting Through Conduit Fitting
Insulated Ground Wire (6) Mounting Studs
Note: NEMA 4 Box not Included by Watlow

Ship Date: 25 Working Days to Ship ARO
F.O.B: (STLOUIS)
Payment Terms: 50% Payment with Purchase Order
50% Net 30Days

*Please Note Terms and Conditions of sale below

Best Regards,
Barry C.

CTA - Critides Technical Associates
Div. of Research Projects, Inc.
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