Published January, 2012

Check for updates

Wheat Growth Response to Increased Temperature from Varied Planting Dates and Supplemental Infrared Heating

M. J. Ottman,* B. A. Kimball, J. W. White, and G. W. Wall

Soil Fertility & Crop Nutrition

ABSTRACT

Possible future increases in atmospheric temperature may threaten wheat (*Triticum aestivum* L.) production and food security. The purpose of this research is to determine the response of wheat growth to supplemental heating and to seasonal air temperature from an unusually wide range of planting dates. A field study was conducted at Maricopa, AZ, where wheat was planted from September to May over a 2-yr period for a total of 12 planting dates. Supplemental heating was provided for 6 of the 12 planting dates using infrared heaters placed above the crop which increased canopy temperature by 1.3°C during the day and 2.7°C during the night. Grain yield declined 42 g m^{-2} (6.9%) per 1°C increase in seasonal temperature above 16.3°C. Supplemental heating had no effect on grain yield for plantings in winter (Dec./Jan.) since temperatures were near optimum (14.9°C). However, in spring (Mar.) plantings where temperature (22.2°C) was above optimum, supplemental heating decreased grain yield from 510 to 368 g m^{-2}. Supplemental heating had the greatest effect in the early fall plantings (Sept./Oct.) when temperature was slightly below optimum (13.8°C) and mid-season frost limited the yield of unheated plots to only 3 g m^{-2} whereas yield of heated plots was 435 g m^{-2}. Thus, possible future increases in temperature may decrease wheat yield for late plantings and shift optimum planting windows to earlier dates in areas of the world similar to the desert southwest of the United States.

Global warming can adversely affect food production and food security according to climate change models (Lobell et al., 2008). The production of wheat may be limited by possible future increases in global temperatures particularly in parts of the world where temperatures for wheat growth are currently optimum (Ortiz et al., 2008; Hatfield et al., 2011). Wheat production affects the health, nutrition, and livelihood of a large percentage of the world's population since more wheat is produced globally than any other crop (FAO, 2010). Thus, the effect of global warming on wheat yields is of prime concern worldwide.

Temperature regimes imposed in controlled environments give some indication of the effects of increased temperature on wheat yield and yield components. In an evaluation of 28 cultivars of wheat in a controlled environment, the optimum temperature for wheat yield was 15°C, and for every 1°C increase above this temperature, grain yields were depressed 3 to 4% (Wardlaw et al., 1989). The reduction in wheat grain yield due to supra-optimal temperatures in studies conducted in controlled environments is associated with reduced kernel weight (Rahman et al., 2009; Gibson and Paulsen, 1999), fewer kernels per spike (Rahman et al., 2009), and lower harvest index (Prasad et al., 2008). However, studies of the effect on increased temperature on wheat yield conducted in controlled environments cannot necessarily be extrapolated to field conditions due to differences in environmental conditions such as solar radiation, air movement, and evaporative demand. Furthermore, controlled-environment studies often underestimate yield losses from temperature effects on plant density and tiller number that would occur under field conditions (Paulsen, 1994).

Planting wheat at various times during the year exposes the crop to different temperatures during its life cycle and can provide an indication of crop response to temperature without artificial conditions imposed by controlled environments. One of the most comprehensive studies of the effect of temperature imposed by planting date on wheat yield was conducted in India where three spring wheat cultivars were evaluated at 10 sowing dates over seven growing seasons (Ortiz-Monasterio et al., 1994). In this study, grain yield, kernel weight, and kernels per m^2 were negatively related to mean temperature at two time periods: (i) 20 d before heading to 10 d after heading and (ii) 10 to 40 d after heading. Many examples can be found in the literature where grain yield of fall to winter-sown spring wheat decreased with later planting dates that exposed the wheat to higher temperatures (Ali et al., 2010; Musick and Dusek, 1980), but correlations between average growing season temperature and yield generally were not examined in these studies. Despite the insights planting date studies can provide in the crop response to temperature, the differing temperatures experienced by a crop in various planting dates are confounded with effects from environmental conditions such as photoperiod, insolation, and water availability and from variation in disease, insect, and weed pressure.

A supplemental heating technique (temperature free-air controlled enhancement [T-FACE]) has recently been developed that can increase temperature in open-field plots without the confounding effects of other environmental factors common to other techniques (Nijs et al., 1996; Kimball, 2005, 2011;

M.J. Ottman, School of Plant Sciences, Univ. of Arizona, P.O. Box 210036, Tucson, AZ 85721; B.A. Kimball, J.W. White, and G.W. Wall, USDA-ARS, U.S. Arid-Land Agricultural Research Center, 21881 N. Cardon Ln., Maricopa, AZ 85138. Received 5 July 2011. *Corresponding author (mottman@ag.arizona.edu).

Published in Agron. J. 104:7–16 (2012)
Posted online 13 Oct 2011
doi:10.2134/agronj2011.0212

Abbreviations: NDVI, normalized difference vegetation index.

Table 1. Experimental details for each planting date of wheat including the treatments (H = heated, C = control with no heaters, R = reference with nonoperable dummy heaters), irrigation amounts, additional irrigation for heated plots which received an average 8% more for irrigation water after the initial irrigation (except for the first crop nominally planted on 13 Mar. 2007), and precipitation and average air temperature between planting and physiological maturity for an experiment conducted at Maricopa, AZ, from 2007 to 2009. The nominal planting date is when seeding occurred, and the effective planting is when the germination irrigation was applied.

Nominal planting date	Effective planting date	Treatments	Irrigation amount	Additional irrigation water for heated plots	Precipitation	Avg. air temperature	Minimum air temperature	Maximum air temperature
			mm			°C		
13 Mar. 2007	21 Mar. 2007	H, C, R	589	0	29	22.8	4.1	39.2
19 Apr. 2007	23 Apr. 2007	C	698	–	7	28.3	9.9	43.3
17 Sept. 2007	26 Sept. 2007	H, C, R	627	28	92	13.9	–4.5	36.0
30 Oct. 2007	1 Nov. 2007	C	781	–	92	13.3	–4.5	35.1
2 Jan. 2008	4 Jan. 2008	H, C, R	922	57	38	15.1	–4.5	35.7
13 Feb. 2008	14 Feb. 2008	C	771	–	52	18.5	0.5	41.9
10 Mar. 2008	14 Mar. 2008	H, C, R	848	56	45	21.6	1.3	41.9
28 Apr. 2008	1 May 2008	C	358	–	45	26.8	6.6	44.5
29 Sept. 2008	7 Oct. 2008	H, C, R	620	27	49	13.7	–2.3	35.8
27 Oct. 2008	30 Oct. 2008	C	822	–	51	13.6	–2.3	33.2
1 Dec. 2008	8 Dec. 2008	H, C, R	802	48	45	14.6	–2.3	36.8
12 Jan. 2009	14 Jan. 2009	C	741	–	15	17.0	–0.8	39.5

Kimball et al., 2008, 2011). This technique employs an array of six infrared heaters placed above the crop in a hexagonal pattern to uniformly heat a 3-m-diam. circular area. The shading from this apparatus is estimated at <1%, and potential changes due to any environmental changes (other than the warming treatment) caused by the apparatus are minimized by comparing "Heated" plots with "Reference" plots that have dummy non-operable heaters. This technique has been used in a variety of locations and species including, but not limited to, perennial ryegrass (*Lolium perenne* L.) in Switzerland (Nijs et al., 1996), sudangrass [*Sorghum sudanense* (Piper) Stapf] in Arizona (Kimball, 2005), and forbs and grasses on the Tibetan Plateau (Luo et al., 2010). However, before the research reported herein, this technique has not been used to determine the effect of increased temperature on the yield of wheat or other food crops.

Thus, the purpose of this study was to determine the effects on wheat growth and yield of supplemental infrared heating and a wide range of temperature imposed by natural seasonal variations achieved by varying planting date. This is part of a series of papers that includes the performance of the T-FACE apparatus itself (Kimball et al., 2011) and the effects of supplemental heating and temperature on wheat phenology (White et al., 2011) and gas exchange and water relations (Wall et al., 2011).

MATERIALS AND METHODS

Study Region

Field studies were conducted to determine the effect of elevated temperature on wheat growth and yield. The studies were conducted from 13 Mar. 2007 through 12 May 2009 at the University of Arizona Maricopa Agricultural Center, Maricopa, AZ (33°4'12" N, 111°58'12" W; 361 m above sea level). The soil was a Trix clay loam (fine-loamy, mixed, superactive, calcareous, hyperthermic Typic Torrifluvent) described by Post et al. (1988).

Crop Culture

The spring wheat 'Yecora Rojo' was sown every 1 to 2 mo, except during the summer, in an effort to grow the crop over a range of growing season temperatures (Table 1). Detailed temperature and other weather data for the duration of the experiment are presented by Wall et al. (2011). Growing wheat during the summer was attempted the first year, but competition from C_4 weeds was intense, and the crop failed due to seedling death. Therefore, no reliable crop growth data could be obtained, so we abandoned this effort in the succeeding summer. Thus, of a total of 15 attempted planting dates, data from 12 are presented herein.

The field plot area had previously been fallow before the present study was initiated. Plantings occurred over a 2-yr period (13 Mar. 2007 through 12 Jan. 2009; Table 1) with a crop sequence of wheat after fallow or wheat after one or two crop seasons of wheat, depending on the sowing date. The field was prepared for each planting as follows: the ground was disked, fertilizer was applied, and the fertilizer was incorporated with a field cultivator. After field preparation, Yecora Rojo hard red spring wheat was seeded into dry soil with a grain drill in rows 19-cm apart at a rate of 134 kg seed ha^{-1} (2.88 million seeds ha^{-1}). The date the seed was drilled into dry soil is the "nominal" planting date, and the "effective" planting date is defined as the date irrigation water was first applied to germinate the seed as described in the section below. Individual seeded blocks were 11 by 11 m in size, and the useable 3-m-diam. plots in the center of the blocks were demarcated using rings of PVC pipe (nominal diameter of 127 mm) where the heating apparatus was erected and plant measurements taken.

Irrigation

A surface drip irrigation system was installed after planting with drip tape placed 38 cm, between every other row. The initial irrigation was intended not only to germinate the seed but also to fill the soil profile to field capacity. After the initial irrigation, water was applied weekly or biweekly based on normalized difference vegetation index (NDVI; Hunsaker et al., 2007). The NDVI was measured two to five times per week using a hand-held radiometer (Model BX-100, Exotech, Inc., Gaithersburg, MD). The experimental area was irrigated with sufficient water to replace potential evapotranspiration less rainfall (Table 1). Following the initial irrigations, the heated plots, which are discussed below, received an average of 8% additional water from a supplemental irrigation system (except for the first planting on 21 Mar. 2007) to account for increased evaporation from these plots and make the infrared heater treatments more equivalent to air heating at constant relative humidity as described by Kimball (2005, 2011) and Wall et al. (2011). The supplemental irrigations were applied at the same time as the larger field irrigations using a secondary small irrigation system superimposed over the larger one.

Fertilization

The amount of fertilizer applied was intended to prevent plant nutrient stresses. Before planting, ammonium phosphate fertilizer (16–20–0) was applied at a rate of 336 kg ha^{-1} providing 54 kg N ha^{-1} and 67 kg P ha^{-1}. During the growing season, urea ammonium nitrate solution (32–0–0) was applied at various growth stages to supply sufficient N for the growth of the crop. The total amount of N applied during the growing season averaged 210 kg N ha^{-1} but varied somewhat depending on the needs of the crop.

Infrared Heating Apparatus

The T-FACE apparatus was placed in the crop every other sowing date (Table 1). The apparatus consisted of six ceramic infrared heaters (1000W, 240V, Mor-FTE; Mor Electric Heating[1], Comstock Park, MI) arranged in a hexagonal array 1.2 m above the canopy as described by Kimball et al. (2008) (Fig. 1). The heaters were suspended from cables in a triangular configuration and were angled 45° from horizontal toward the center of the plot. The heaters were raised weekly as the crop grew to maintain a height of 1.2 m above the top of the wheat canopy. Canopy temperature was sensed using infrared thermometers (Model IRR-PN[1], Apogee Instruments Inc., Logan, UT), and the heaters were controlled to achieve target canopy temperature increases in the heated compared to the reference plots of 1.5°C during the day and 3.0°C during the night. The night temperature was still cooler than the day temperature. The mean increase in canopy temperature obtained over the course of this study were 1.3°C during the day and 2.7°C during the night (Wall et al., 2011), although the mode increase in canopy temperature were within 0.1°C of the targets (Kimball et al. (2011).) The season-long mean canopy temperature increases were smaller than the target temperature increases because the apparatus could not supply enough heat during windy periods. Another reason is that, as will be discussed later in more detail, the fall-planted wheat experienced frosts that damaged the unheated wheat with consequent reduction in evapotranspirational cooling, so that during the daytime following the frosts, the heated plots from these two plantings were cooler than the corresponding reference plots even with the heaters fully on.

Crop Growth Measurements

Each crop was sampled three times during the growing seasons for biomass and other crop growth parameters. The stages at sampling were before flag leaf emergence, after heading, and final harvest between physiological maturity and harvest ripe stage. An exception to the stages at sampling is the first sampling of the 21 Mar. 2008 planting which occurred between anthesis and the kernel milky stage. The first two samples taken during

[1] Company names are included for the benefit of the reader and do not imply any special endorsement by the U.S. Department of Agriculture or the University of Arizona.

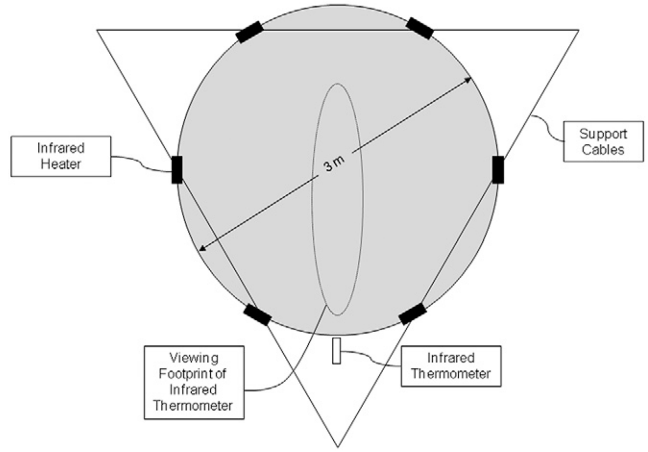

Fig. 1. Schematic diagram of the supplemental heating apparatus showing the infrared heaters, their support cables, and 3-m-diam. heating area for an experiment conducted at Maricopa, AZ, from 2007 to 2009. Also pictured are the infrared thermometer and its viewing footprint.

the growing season were from four rows, 0.46 m in length for an area of 0.35 m^2. These samples were taken toward the edges of the 3-m-diam. plots so as not to affect the final harvest areas near the centers of the plots (Fig. 1). The final samples taken at harvest were from five rows, 1.0 m in length for an area of 0.95 m^2. The final harvest areas received no foot traffic during the growing season, and each encompassed a large portion of the viewing footprints of the infrared thermometers (Fig. 1).

Plant biomass was estimated from the samples by drying in an oven at 65°C. The numbers of plants in the samples were counted, and from a subsample of 5 to 10 plants, plant heights and numbers of stems and spikes were measured. For the first two sampling times, areas and weights of stems, green leaves, brown leaves, spikes, and crowns (weight only) were determined. The yield of stems, green leaves, brown leaves, spikes, and crowns was determined from the relative weights of these plant parts in a sample of 5 to 10 plants multiplied by the yield of the whole plant sample. Area of various plant organs was measured using a LI-COR (Lincoln, NE) leaf area meter. Stem and spike area index were calculated assuming that these organs were cylindrical in shape, and leaf area index was calculated assuming the leaves were flat in shape. Plant area index was calculated from the sum of leaf, stem, and spike area. For the final harvest, grain weight, kernel weight, grain volume weight, and grain moisture were determined. Grain and total plant yield were adjusted to a 0% moisture basis. Harvest index was calculated as the ratio of grain yield to total plant yield.

Experimental Design and Statistical Analysis

The effects of temperature on wheat growth were studied using supplemental heating and natural differences in growing season temperature from differing planting dates. Supplemental heating was applied to 6 of the 12 planting dates (Table 1). The experimental design for the supplemental heating study was a 3 by 3 Latin square for six planting dates (Table 1). The three treatments were: (i) heated – average canopy temperature increase of 1.3°C during the day and 2.7°C during the night compared to the reference plots, (ii) reference–heating apparatus erected but with nonoperable dummy heaters, (iii) control–no heating and no heating apparatus erected. Reference

Table 2. Coefficient of determination (R^2) for wheat yield and yield components regressed against a second degree polynomial of air or canopy temperature all season, preanthesis, or postanthesis for an experiment conducted at Maricopa, AZ, from 2007 to 2009.

		Coefficient of determination (R^2)†											
Temperature	Time period	Total yield	Grain yield	Straw yield	Harvest index	Kernel weight	Kernels per spike	Plant density	Stem density	Stems per plant	Spike density	Barren stems	Plant height
Air	all season	0.94**	0.75**	0.93**	0.32ns†	0.67*	0.52ns	0.39ns	0.42ns	0.19ns	0.18ns	0.90**	0.93**
	preanthesis	0.93**	0.71*	0.91**	0.21ns	0.64*	0.48ns	0.36ns	0.45ns	0.20ns	0.14ns	0.90**	0.92**
	postanthesis	0.92**	0.86**	0.93**	0.71*	0.82**	0.63*	0.45ns	0.34ns	0.21ns	0.14ns	0.74**	0.85**
Canopy	all season	0.78*	0.65ns	0.85**	0.61ns	0.88**	0.61ns	0.65ns	0.50ns	0.31ns	0.27ns	0.90**	0.90**
	preanthesis	0.96**	0.91**	0.98**	0.69ns	0.92**	0.68ns	0.80*	0.49ns	0.21ns	0.20ns	0.86**	0.94**
	postanthesis	0.93**	0.85**	0.96**	0.69ns	0.93**	0.71*	0.72*	0.46ns	0.39ns	0.27ns	0.92**	0.99**

* Significant at $P = 0.05$.
** Significant at $P = 0.01$.
† ns = not significant at $P = 0.05$.

and control treatments were similar, so they were pooled in the analysis and referred to as the "unheated" treatment.

Wheat was planted from September to May over a 2-yr period (Table 1) for a total of 12 planting dates for the purposes of growing wheat over a range of temperatures. The experimental design for this planting date study was 12 planting dates replicated three times. However, only 10 planting dates were used since the grain from the early fall planting dates (26 Sept. 2007 and 7 Oct. 2008) failed to develop due to cold (frost) injury. The air temperatures from planting to anthesis, anthesis to physiological maturity, and planting to physiological maturity were averaged and related to yield and yield components. Anthesis was chosen as a demarcation point in the season since it is a recognizable phenological stage and marks the beginning of grain fill. Canopy temperature was recorded in the supplemental heating study for six planting dates for the heated and reference plots, but data from the two fall planting dates was excluded from the analysis. The reference and control plots were pooled and referred to as "unheated" in the planting date study as was done in the supplemental heating study.

The effect of supplemental heating was analyzed using the MIXED procedure, and the effect of temperature from the various planting dates was analyzed using a second degree polynomial in the REG procedure in SAS (SAS Institute, 2009). Decreases in total, grain, and straw yield per 1°C increase in temperature were calculated from the slope of the first degree polynomial. Since grain yield (unlike total and straw yield) reached a peak with temperature in our study, we calculated the decrease in grain yield per 1°C increase in temperature above the temperature where peak grain yield was achieved. The temperature at peak grain yield was calculated from the first derivative of the quadratic function set to zero and solved for temperature.

RESULTS AND DISCUSSION

Planting Dates and Growing Season Temperature

Yield and many yield components were related to growing season temperature (Table 2). This relationship was detected for both temperature measurements (air and canopy) and for all growth periods (preanthesis, postanthesis, and all season). Temperature had a negative influence on yield and many yield components regardless of the temperature measured (air or canopy) or the growth period. The coefficients of determination (R^2) were generally highest for air temperature measured postanthesis, so graphs of the relation between temperature and yield and yield components are presented for air temperature measured postanthesis only (Fig. 2 and 3).

The relationship between temperature and yield was particularly strong. The coefficients of determination (R^2) for postanthesis air temperature were 0.92 for total yield, 0.93 for straw yield, and 0.86 for grain yield. The relationships between temperature and total, grain, and straw yield were negative, although the response of grain yield was more quadratic than that for total and straw yield. Grain yield peaked before decreasing with temperature, whereas total and straw yield decreased continuously with temperature within the temperature range of this study. Grain yield decreased by 45 g m^{-2} (about 7.1%) per 1°C increase in postanthesis air temperature above 21.9°C. Total and straw yield did not peak in the temperature range of our study, but total yield decreased by 85 g m^{-2} (4.4%) and straw yield decreased by 58 g m^{-2} (4.7%) per 1°C increase in postanthesis air temperature above 16.9°C. The yield decreases for temperature averaged over the entire season were similar to the results from postanthesis air temperature, although grain yield peaked at a lower temperature. Using air temperature averaged over the entire season, grain yield decreased by 42 g m^{-2} (6.9%) per 1°C increase temperature above 16.3°C and total yield decreased by 91 g m^{-2} (5.0%) and straw yield decreased by 61 g m^{-2} (4.9%) per 1°C increase in temperature above 13.3°C.

Some of the components of yield responded to temperature in a similar manner to yield itself, as might be expected. Harvest index, the proportion of grain to total yield, reached a peak before decreasing similar to grain yield, although the peak occurred at 25.3°C, higher than the postanthesis air temperature of 21.9°C where grain yield peaked. Kernels per spike peaked at an average postanthesis air temperature 23.1°C, slightly higher than that for grain yield, before decreasing with temperature. Unlike harvest index and kernels per spike, kernel weight decreased with temperature in a very linear fashion without a peak in the range of temperatures in this study. The proportion of barren stems decreased with temperature to 31.1°C before leveling off, which is interesting. Apparently, excess tillering occurs at lower temperatures, which are more optimal for wheat growth, but coincidentally produce barren stems. Plant height decreased with temperature in a strongly linear fashion similar to total and straw yield. Plant density was not related to temperature, which is somewhat expected since the seeding rate was constant, but stand loss still could have occurred at temperatures lower or higher than optimum. Stem density and stems per plant were not affected by temperature. Spike density was also not related to temperature suggesting that kernel weight

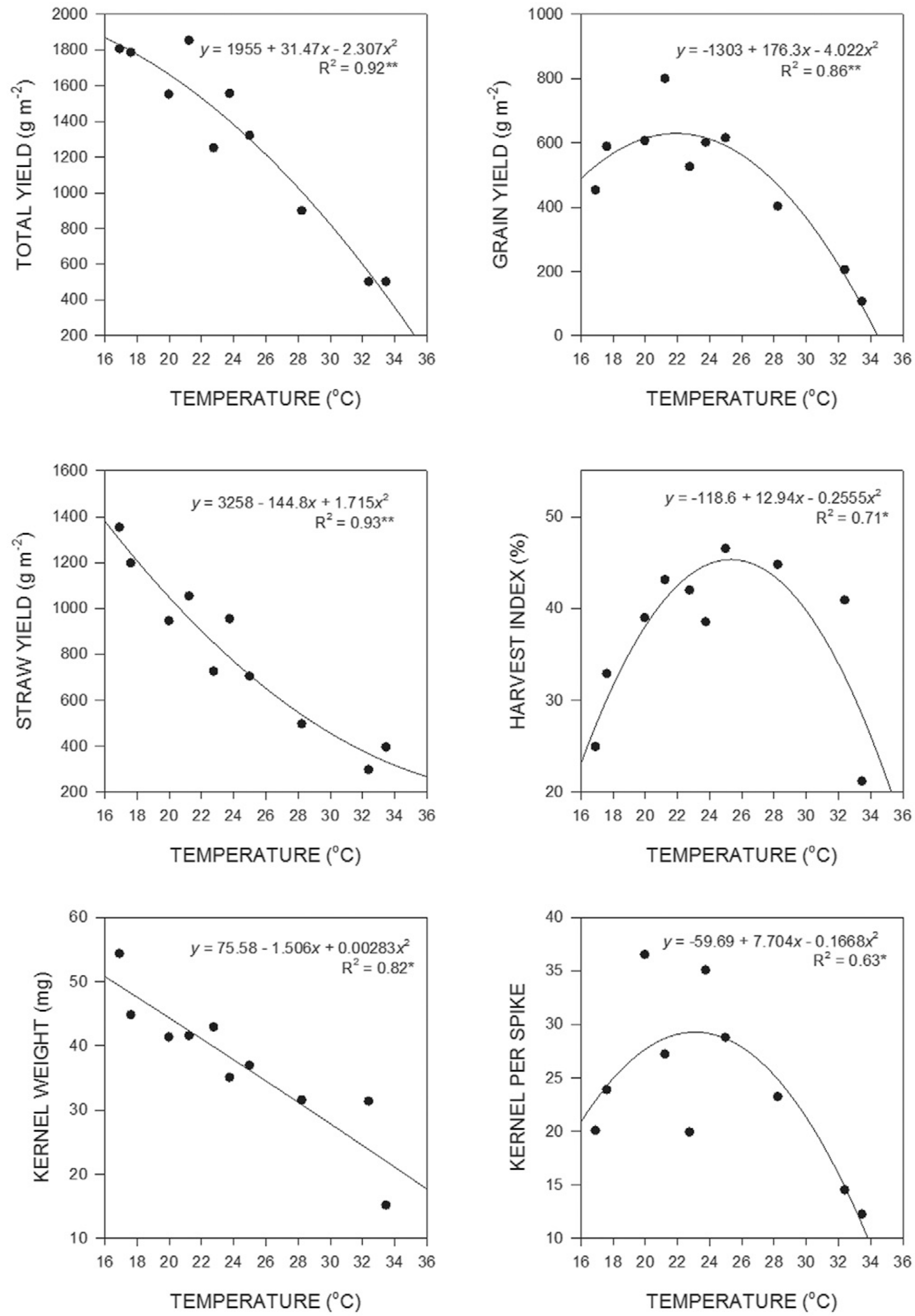

Fig. 2. Influence of average air temperature after anthesis for 10 planting dates on wheat total yield, grain yield, straw yield, harvest index, kernel weight, and kernels per spike for the unheated plots for an experiment conducted at Maricopa, AZ, from 2007 to 2009.

and spike size (kernels per spike) are more accurate predictors of grain yield response to temperature than spike density.

The relative ability of various temperature measurements to predict yield and yield components generally did not differ (Table 2). Air and canopy temperatures averaged over the entire season, preanthesis, and postanthesis resulted in R^2 values that did not differ from each other statistically. The confidence limits for R^2 values are very wide if based on 10 air temperature observations or eight canopy temperature observations, and perhaps differences would be detected in an analysis based on more observations. Nevertheless, our various temperature measurements are correlated with each other and not independent, so the fact that similar results were obtained using differing measures of temperature is not surprising. The least that can be noted in terms of differences from these temperature measurements is that (i) harvest index was related to postanthesis air temperature but not air temperature averaged over other intervals or to canopy temperature at any time, (ii) kernels per spike was related to air or canopy temperature postanthesis but not at other times, and (iii) plant density was related to pre- and postanthesis canopy temperature only. For all other measures of yield and yield components, the specific temperature measurements produced similar results.

Many planting date studies have been conducted with wheat, but few have correlated yield with growing season temperature for each planting date. Typically, yield is optimized at a particular planting date window for a growing region, and yield

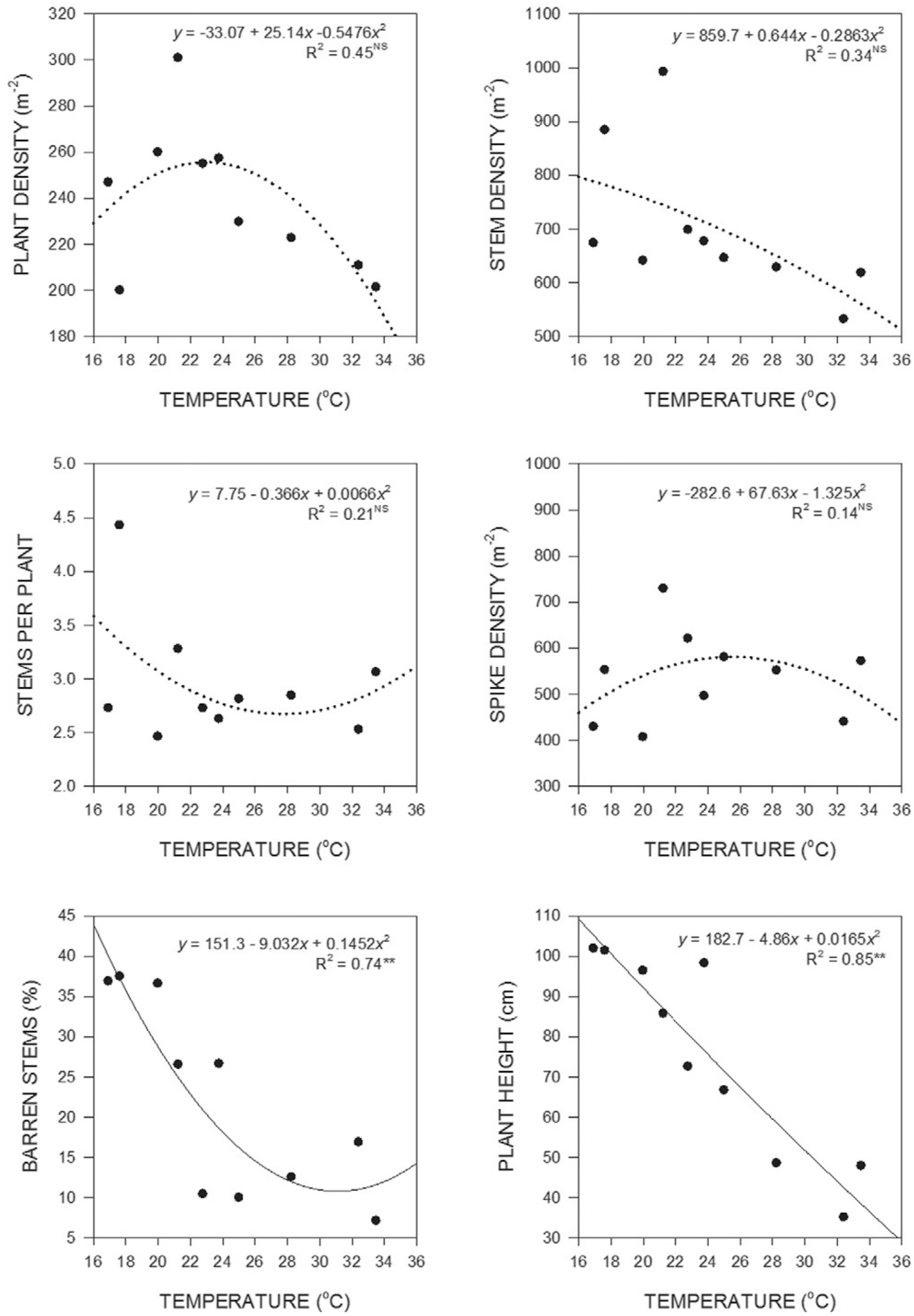

Fig. 3. Influence of average air temperature after anthesis for 10 planting dates on wheat plant density, stem density, stems per plant, spike density, barren stems, and plant height for the unheated plots for an experiment conducted at Maricopa, AZ, from 2007 to 2009.

decreases with plantings earlier or later than this optimum time. The reason yields are optimized at a particular planting time could be due to favorable temperatures during the growing season or to factors such as water availability or lack of pest problems. Regardless of the environmental factors or growing conditions responsible for yield optimization at specific planting times, yield maximization has been associated with increases in tillering during vegetative growth (Musick and Dusek, 1980) and tillers at harvest (El-Gizawy, 2009), dry matter yields (Musick and Dusek, 1980), spikes per m^2 (Rocheford et al., 1988; El-Gizawy, 2009), and kernel weight (El-Gizawy, 2009). In a planting date study where the mean daily high temperature from anthesis to maturity was 25, 28, and 31°C for the first, second, and third planting, respectively, yield was correlated with harvest index, kernel weight, kernel number, and spike density for most plantings (Ouabbou and Paulsen, 2000). However, the direct relationship between temperature and yield and its components was not reported in this study. In the study of Ortiz-Monasterio et al. (1994), a direct relationship between temperature for various planting dates and yield, kernel weight, and kernels per m^2 was reported. In their study, the mean daily temperature was not calculated for the entire growing season but for a time period near anthesis and a second time period during grain fill.

The studies described above are not fully comparable to the present study, but are similar in the aspect that yield is maximized at a particular planting window and temperature or

Table 3. **Wheat yield and yield components at maturity as affected by supplemental infrared heating for various planting times for an experiment conducted at Maricopa, AZ, from 2007 to 2009.**

Planting season	Planting date	Heating	Total yield	Grain yield	Straw yield	Harvest index	Kernel weight	Kernels per spike	Plant density	Stem density	Stems per plant	Spike density	Barren stems	Plant height
			g m^{-2}			%	mg		m^{-2}			m^{-2}	%	cm
Fall	26 Sept. 2007	No	894	0	894	0	–	–	260	1328	5.18	673	48.8	84.8
		Yes	1175	348	827	30.1	41.6	14.8	236	710	3.03	568	20.0	78.7
			**	*	ns†	*	–	–	ns	**	**	ns	*	ns
	7 Oct. 2008	No	1428	6	1422	0.4	31.7	0.2	213	993	4.67	843	15.3	95.3
		Yes	1410	522	887	37.1	48.3	16.5	269	769	2.87	662	14.1	88.0
			ns	**	**	**	**	**	**	*	**	ns	ns	**
Winter	4 Jan. 2008	No	1854	800	1054	43.2	41.6	27.2	301	993	3.28	730	26.6	85.8
		Yes	1686	716	969	42.3	44.1	27.4	285	858	3.00	613	29.6	86.3
			ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns
	8 Dec. 2008	No	1553	606	946	39.0	41.4	36.5	260	642	2.47	408	36.6	96.5
		Yes	1658	667	991	40.2	41.4	38.7	274	731	2.67	441	40.3	95.0
			ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Spring	21 Mar. 2007	No	901	403	498	44.8	31.6	23.3	223	629	2.85	553	12.6	48.7
		Yes	605	270	335	43.6	29.4	18.6	212	541	2.57	480	10.9	41.0
			*	*	*	ns	ns	**	ns	ns	ns	ns	ns	**
	14 Mar. 2008	No	1322	616	706	46.5	36.9	28.8	230	647	2.82	581	10.1	66.8
		Yes	1079	466	612	43.2	36.3	21.0	199	702	3.53	622	11.3	64.3
			**	**	*	**	ns	*	*	ns	**	ns	ns	ns

* Significant at $P = 0.05$.
** Significant at $P = 0.01$.
† ns = not significant at $P = 0.05$.

yield is related to total yield, harvest index, and kernel weight. In our study, mean growing season temperature (and yield) did not affect stems per plant or spike density in contrast to the studies mentioned above. Stems per plant and spike density are determined earlier in the crop growth cycle than kernel weight, so the fact that these yield components were not affected by temperature in our study indicates that the temperatures were closer to optimum early in the growth cycle but were higher than optimum later. The study of Ortiz-Monasterio et al. (1994) is perhaps most similar to ours since we both found a negative correlation between temperature and yield and kernel size, although we used temperatures from the entire growing season, and they used temperatures near anthesis and during grain fill.

Supplemental Heating

The influence of supplemental heating on yield and its components depended greatly on the season in which planting occurred (Table 3). Supplemental heating had no effect on yield and yield components for winter plantings except for a slight decrease in straw yield for one of the planting dates. Wheat is normally planted in the winter in the region where this study was conducted, and therefore, temperature increases similar to those provided by our infrared heaters may not affect future wheat production for winter-sown wheat. However, supplemental heating had a considerable effect on yield and yield components for early plantings in the fall and late plantings in the spring.

Yield was reduced by heating in both spring plantings. The reduction in total, grain, and straw yield averaged 26, 29, and 23%, respectively. Heating also reduced harvest index from 46.5 to 43.2% in the 14 Mar. 2008 planting. The yield component that was primarily responsible for the grain yield decrease with heating for the spring plantings was the number of kernels per spike, which was decreased by 24%. Kernel weight, stem density, spike density, and barren stems were not affected by heating. For the 14 Mar. 2008 planting, plant density was decreased by heating, but this was compensated for by an increase in stems per plant. However, the increase in the number of stems per plant in the heated plots was not able to compensate for the loss in kernels per spike. Plant height was decreased by heating in the spring planting in 2007, but not in 2008.

The most dramatic effect of heating on yield occurred in the two early plantings in the fall (26 Sept. 2007 and 7 Oct. 2008). Supplemental heating during these seasons protected the grain from cold damage and allowed it to develop and mature (Fig. 4). In contrast, the plots without heating produced little or no grain in the fall planting season. Grain yield was increased by heating in the fall

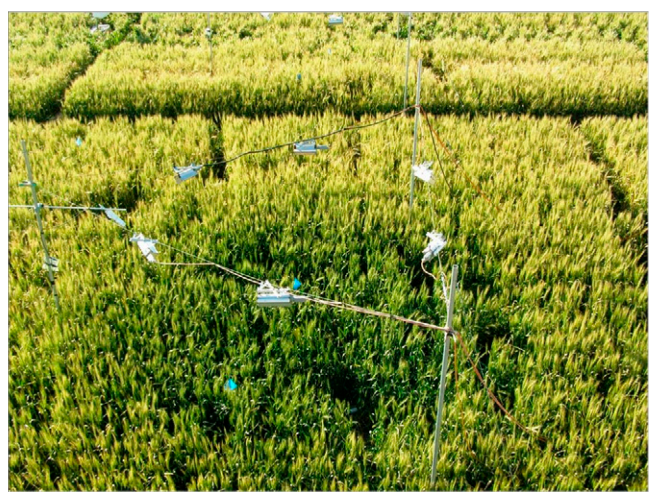

Fig. 4. Photograph taken on 10 Jan. 2008 after subfreezing temperature 2 wk earlier of wheat planted on 26 Sept. 2007. The wheat crop inside the 3-m diam. heated area was not damaged by the frosts (darker color) as contrasted with the unheated area (lighter color).

plantings from 0 to 348 g m^{-2} in 2007 and from 6 to 522 g m^{-2} in 2008. Total yield was increased by heating by 31% in 2007 but was not affected in 2008 since the increase in grain yield was matched by a decrease in straw yield of a similar magnitude. Harvest index was increased dramatically by heating since grain yield is part of the calculation. Heating in the fall planting season increased kernel weight, kernels per spike, and plant density (in 2008) but decreased stem density and stems per plant. Spike density was not affected by heating in the fall planting season, but heating reduced barren stems in 2007 and shortened plant height in 2008.

The effect of supplemental heating on total biomass yield sampled at various times during the growing season varied depending on the planting date (Table 4). During the winter planting season, heating resulted in an increase in total biomass yield in two out of four combinations of planting and sampling dates. During the fall planting season, heating increased total biomass yield at the second sampling of the 7 Oct. 2008 planting date. During the spring planting season, heating decreased total biomass yield in one out of four combinations of planting and sampling dates and increased biomass yield in one case. In summary, heating increased total biomass yield at five sampling times, decreased biomass yield at one sampling times for a spring planting, and had no effect at six sampling times.

In cases where heating had an effect on total biomass yield, the yield of leaves, stems, and spikes increased or decreased in a corresponding manner except for (i) the 12 Jan. 2009 sampling of the 7 Oct. 2008 planting where supplemental heating increased total yield but decreased the yield of green leaves and (ii) the 13 May 2008 sampling of the 14 Mar. 2008 planting where supplemental heating increased total yield but decreased the yield of green leaves and the crown. In two out of the six cases where heating had no effect on total biomass yield, heating also had no effect on the yield of leaves, stems, spikes, and crowns. However, in four cases where we were unable to detect an effect of heating on total biomass yield, we did detect an increase in spike yield (19 Dec. 2007 sampling of 26 Sept. 2007 planting), an increase in spike yield and decrease in stem and green leaf yield (6 Apr. 2009 sampling of 8 Dec. 2008 planting), an increase in stem yield (25 Apr. 2007 sampling of 21 Mar. 2007 planting), and a decrease in spike yield (3 June 2008 sampling of 14 Mar. 2008 planting).

The effect of heating on the yield of green leaves, stems, spikes, crowns, and brown leaves varied according to planting and sampling date. Heating increased the yield of green leaves at one sampling time for a winter planting and decreased the yield of green leaves at one sampling time each for a fall, winter, and spring planting. Stem yield was increased by supplemental heating at the first sampling but decreased by heating at the second sampling of two planting dates. Spike yield was increased by heating in five cases represented by all the planting seasons, but was also decreased in the 3 June 2008 sampling of the 14 Mar. 2008 planting date. This measured increase in spike yield may be an artifact since the heated treatments were generally at a more advanced stage at the time of sampling and the spikes more developed than the corresponding unheated plots. Heating had no effect on yield of the crown for any of the sampling times except for the 13 May 2008 sampling of the 14 Mar. 2008 planting date. Heating did not have an effect on the yield of brown leaves except for the decrease in the yield of brown leaves measured at the 6 Apr. 2009 sampling of the 8 Dec. 2008 planting.

Biomass yield components offer further explanations for the observed effects of heating on total biomass yield. For the winter planting season, plant and stem density and stems per plant were generally unaffected by heating. The exception was at the 4 Jan. 2008 planting date where stems per plant were decreased at the second sampling time. Plant height was increased by heating at two of the sampling times at different planting dates during the winter indicating a positive effect of heating on growth. For the spring planting season, plant and stem density, stems per plant, and plant height were not affected by heating. The exception was a decrease in stem density observed at the first sampling time of the 21 Mar. 2007 planting date. For the fall planting season, we were not able to detect an effect of heating on plant density, stem density, or stems per plant except for an increase in stem density for the 23 Oct. 2007 sampling of the 26 Sept. 2007 planting. However, we did measure an increase in plant height due to heating at the 12 Jan. 2009 sampling of the 7 Oct. 2008 planting date where we also measured an increase in total biomass.

The areas of leaves, stems, and heads were affected by supplemental heating similar to the response of biomass. We were able to detect an influence of heating on the area of these various plant parts only at planting dates where a difference in biomass was also detected. Plant area was less sensitive to heating effects than biomass since differences in biomass were detected at some planting dates where differences in plant area were not detected. For the fall planting season, heating resulted in an increase in stem area at the first sampling of the 7 Oct. 2008 planting. For the winter planting season, area of leaves and stems was increased by heating at the first sampling of the 8 Dec. 2008 planting date. For the spring planting season, leaf area was decreased by heating at the first sampling of the 21 Mar. 2007 planting date and spike area was decreased by heating at the second sampling of the 14 Mar. 2008 planting date.

Interpretation of the effect of heating on biomass yield, yield components, and plant area during the growing season is complicated by the fact that heating accelerated plant development, so those plots receiving supplemental heating were at a more advanced stage at the time of sampling. During the fall planting season, supplemental heating had a positive effect on biomass yield one year which might be expected since the plants were maturing in the winter. During the winter planting season, supplemental heating had a positive influence on growth and development during the growing season, but these differences were not detectable at maturity. During the spring planting season, the negative effects of supplemental heating were detected at only one sampling time (but a positive effect of heating was detected at another sampling time) perhaps because any negative effect of heating was masked by the more advanced stage of the heated plots at the time of sampling.

Studies conducted in controlled environments have reported reduction in wheat grain yield due to supra-optimal temperatures (Gibson and Paulsen, 1999; Rahman et al., 2009; Prasad et al., 2008). The reduction in grain yield in these studies is related to reduced green leaf area and productive tillers per plant (Rahman et al., 2009), reduced kernel weight (Rahman et al., 2009; Gibson and Paulsen, 1999), fewer kernels per spike (Rahman et al., 2009), and lower harvest index (Prasad et al., 2008). In our field study, yield and various yield components declined due to supra-optimal temperatures from supplemental heating. However, this occurred only

Table 4. Wheat biomass yield, yield components, and areas of various plant parts at two growth stages before harvest as affected by supplemental infrared heating for various planting times for an experiment conducted at Maricopa, AZ, from 2007 to 2009.

Planting season	Planting date	Sampling date	Growth stage	Heating	Yield Total	Yield Green leaf	Yield Stem	Yield Spike	Yield Crown	Yield Brown leaf	Plant density	Stem density	Stems per plant	Plant height	Area Leaf	Area Stem	Area Spike	Area Total
					g m^{-2}						m^{-2}			cm	m^2 m^{-2}			
Fall	26 Sept. 2007	23 Oct. 2007	5–6 leaf	No	92	63	22	0	4.6	2.6	302	1006	3.33	25.9	2.10	0.25	0.00	2.35
			6 leaf	Yes	93	61	23	0	8.0	1.2	300	1080	3.60	25.2	2.49	0.28	0.00	2.77
					ns†	ns	ns	–	ns	ns	ns	*	ns	ns	ns	ns	–	ns
		19 Dec. 2007	anthesis	No	784	174	409	141	24.8	34.8	290	927	3.20	87.2	4.58	1.40	0.61	6.59
			milk	Yes	887	139	425	243	21.7	58.5	290	910	3.13	85.0	3.16	1.49	0.66	5.31
					ns	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	7 Oct. 2008	13 Nov. 2008	1–2 nodes	No	140	86	42	0	8.9	2.9	300	1026	3.40	38.6	3.37	0.29	0.00	3.66
			2 nodes	Yes	154	89	54	0	7.2	4.5	314	1089	3.47	40.0	4.12	0.40	0.00	4.52
					ns	ns	ns	–	ns	ns	ns	ns	ns	ns	ns	*	–	ns
		12 Jan. 2009	headed	No	668	146	342	101	23.6	55.3	371	833	2.23	74.3	3.39	1.24	0.55	5.19
			milk	Yes	763	109	386	200	21.6	44.9	344	742	2.13	79.8	2.38	1.24	0.67	4.29
					*	*	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Winter	4 Jan. 2008	18 Mar. 2008	flag leaf	No	547	190	239	0	34.7	82.2	306	1307	4.37	55.2	6.29	0.91	0.00	7.20
			boot	Yes	660	209	313	0	33.3	105.0	278	1008	3.73	62.0	5.10	0.88	0.00	5.98
					*	ns	ns	–	ns	ns	ns	ns	ns	*	ns	ns	–	ns
		15 Apr. 2008	water	No	1415	251	646	369	49.6	99.2	291	1004	3.47	90.0	3.52	1.87	0.73	6.12
			milk	Yes	1603	231	670	561	47.8	93.1	291	892	3.07	89.0	3.30	1.81	0.84	5.96
					*	ns	ns	*	ns	ns	ns	ns	*	ns	ns	ns	ns	ns
	8 Dec. 2008	26 Jan. 2009	5 leaf	No	97	68	24	0	4.7	0.0	378	1087	2.93	33.5	1.68	0.20	0.00	1.87
			1 node	Yes	162	111	47	0	3.9	0.0	387	1222	3.13	39.3	3.26	0.35	0.00	3.61
					**	**	**	–	ns	–	ns	ns	ns	**	**	**	–	**
		6 Apr. 2009	water	No	1392	266	629	347	40.2	109.0	326	812	2.50	95.2	4.34	1.63	0.65	6.62
			milk	Yes	1433	195	573	557	37.4	70.2	305	731	2.40	97.7	3.89	1.54	0.82	6.25
					ns	*	**	**	ns	*	ns	ns	ns	ns	ns	ns	ns	ns
Spring	21 Mar. 2007	25 Apr. 2007	3 nodes	No	151	80	57	0	10.7	3.0	233	862	3.72	31.2	2.42	0.30	0.00	2.72
			flag leaf	Yes	179	86	79	0	8.7	4.7	222	786	3.57	30.7	1.99	0.28	0.00	2.27
					ns	ns	*	–	ns	ns	ns	*	ns	ns	*	ns	–	*
		21 May 2007	water	No	763	42	243	379	18.4	82.1	266	759	2.83	55.9	0.67	0.99	0.84	2.50
			milk	Yes	645	25	174	373	13.4	60.8	265	860	3.27	50.8	0.55	0.85	0.89	2.29
					*	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	14 Mar. 2008	13 May 2008	anthesis	No	869	186	366	227	27.8	62.1	282	1081	3.83	70.0	3.70	1.35	0.76	5.81
			milk	Yes	948	166	374	329	26.3	51.6	271	981	3.60	67.0	3.35	1.15	0.74	5.25
					*	*	ns	**	*	ns	ns	ns	ns	ns	ns	ns	ns	ns
		3 June 2008	s. dough	No	1439	84	351	879	31.9	92.2	286	954	3.37	69.8	1.09	1.29	0.90	3.29
			h. dough	Yes	1268	50	310	792	27.8	87.4	268	949	3.53	66.0	0.56	1.15	0.87	2.59
					ns	ns	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	**	ns

* Significant at $P = 0.05$.
** Significant at $P = 0.01$.
† ns = not significant at $P = 0.05$.

in the spring planting season where the growing season temperature averaged 22.8 and 21.6°C for the first and second spring plantings, respectively. During the winter planting season, the growing season temperature averaged 15.1 and 14.6°C for the first and second winter plantings, respectively. The temperature increase from supplemental heating of 1.3°C during the day and 2.7°C during the night apparently was not enough to tip the temperature into the supra-optimal range. The optimum temperature for wheat above which yield decreases has been reported to be 15°C (Chowdhury and Wardlaw, 1978; Wardlaw et al., 1989). Temperatures during the fall planting times averaged 13.9 and 13.7°C for the first and second fall plantings, respectively, similar to the winter planting times, but cold temperatures lethal to grain development occurred later in the season when the grain was developing. During the winter planting times, these low temperatures occurred earlier in the season during tillering and jointing, previous to the stages where the grain can be damaged by low temperature. Supplemental heating for the fall planting, therefore, allowed the kernels to develop.

CONCLUSIONS

This study suggests that possible future increases in global temperature could have a negative, neutral, or positive effect on spring wheat yield. Temperature increases can have negative effect on wheat yield in regions where temperatures currently are near or above the optimum. In regions where growing season temperatures are near optimal and well below supra-optimal, future temperature increases may have no effect on wheat yield. Surprisingly, a relatively small temperature increase may dramatically increase yields in regions that receive lethal cold temperature during critical stages of grain development. A slight temperature increase may allow wheat planting to occur earlier as has been reported in Montana, for example (Lanning et al., 2010), and shift the timing of entire cropping systems.

ACKNOWLEDGMENTS

The technical assistance of Mary Comeau in processing the plant samples is greatly appreciated as well as the assistance provided by Charles Blackshear, Matt Conley, Steve Farnsworth, Justin Laughridge, Laura M. Olivieri, and Dr. Zahra Troeh. This research was supported by the Agricultural Research Service, U.S. Department of Agriculture.

REFERENCES

Ali, M.A., M. Ali, M. Sattar, and L. Ali. 2010. Sowing date effect on yield of different wheat varieties. J. Agric. Res. 48:157–162.

Chowdhury, S.I., and I.F. Wardlaw. 1978. The effect of temperature on kernel development in cereals. Aust. J. Agric. Res. 29:205–233. doi:10.1071/AR9780205

El-Gizawy, N.Kh.B. 2009. Effect of planting date and fertilizer application on yield of wheat under no till system. World J. Agric. Sci. 5(6):777–783.

FAO, Food and Agriculture Organization of the United Nations. 2010. *In* Statistics–FAOSTAT–Agriculture. Available at http://www.fao.org (accessed 3 Sept. 2010; verified 30 Sept. 2011). FAO, Rome.

Gibson, L.R., and G.M. Paulsen. 1999. Yield components of wheat grown under high temperature stress during reproductive growth. Crop Sci. 39:1841–1846. doi:10.2135/cropsci1999.3961841x

Hatfield, J., K. Boote, B.A. Kimball, L.H. Ziska, R.C. Izaurralde, D. Ort, A.M. Thomson, and D. Wolfe. 2011. Climate effects on agriculture: Implications for crop production. Agron. J. 103:351–370.

Hunsaker, D.J., G.J. Fitzgerald, A.N. French, T.R. Clarke, M.J. Ottman, and P.J. Pinter, Jr. 2007. Wheat irrigation management using multispectral crop coefficients: I. crop evapotranspiration prediction. Trans. ASABE 50:2017–2033.

Kimball, B.A. 2005. Theory and performance of an infrared heater for ecosystem warming. Glob. Change Biol. 11:2041–2056.

Kimball, B.A. 2011. Comment on the comment by Amthor et al. on "Appropriate experimental ecosystem warming methods" by Aronson and McNulty. Agric. For. Meteorol. 151:420–424. doi:10.1016/j.agrformet.2010.11.013

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. Glob. Change Biol. 14:309–320. doi:10.1111/j.1365-2486.2007.01486.x

Kimball, B.A., J.W. White, M.J. Ottman, G.W. Wall, C.J. Bernacchi, J. Morgan, and D.P. Smith. 2011. Predicting canopy temperatures and infrared heater energy requirements for warming field plots. Agric. For. Meteorol.

Lanning, S.P., K. Kephart, G.R. Carlson, J.E. Eckhoff, R.N. Stougaard, D.M. Wichman, J.M. Martin, and L.E. Talbert. 2010. Climatic change and agronomic performance of hard red spring wheat from 1950 to 2007. Crop Sci. 50:835–841. doi:10.2135/cropsci2009.06.0314

Lobell, D.B., M.B. Burke, C. Tebaldi, M.D. Mastrandrea, W.P. Falcon, and R.L. Naylor. 2008. Prioritizing climate change adaptation needs for food security in 2030. Science (Washington, DC) 319:607–610. doi:10.1126/science.1152339

Luo, C., G. Xu, Z. Chao, S. Wang, X. Lin, Y. Hu, et al. 2010. Effect of warming and grazing on litter mass loss and temperature sensitivity of litter and dung mass loss on the Tibetan plateau. Glob. Change Biol. 16:1606–1617. doi:10.1111/j.1365-2486.2009.02026.x

Musick, J.T., and D.A. Dusek. 1980. Planting date and water deficit effects on development and yield of irrigated winter wheat. Agron. J. 72:45–52. doi:10.2134/agronj1980.00021962007200010010x

Nijs, I., H. Teughels, H. Blum, G. Hendrey, and I. Impens. 1996. Simulation of climate change with infrared heaters reduces the productivity of *Lolium perenne* L. in summer. Environ. Exp. Bot. 36:271–280. doi:10.1016/0098-8472(96)01021-0

Ortiz, R., K.D. Sayre, B. Govaerts, R. Gupta, G.V. Subbarao, T. Ban, D. Hodson, J.M. Dixon, J.I. Ortiz-Monasterio, and M. Reynolds. 2008. Climate change: Can wheat beat the heat? Agric. Ecosyst. Environ. 126:46–58. doi:10.1016/j.agee.2008.01.019

Ortiz-Monasterio, J.I., S.S. Dhillon, and R.A. Fischer. 1994. Date of sowing effects on grain yield and yield components of irrigated spring wheat cultivars and relationships with radiation and temperature in Ludhiana, India. Field Crops Res. 37:169–184. doi:10.1016/0378-4290(94)90096-5

Ouabbou, H., and G.M. Paulsen. 2000. Evaluation of selection criteria for performance of wheat cultivars during high temperature stress in the field. p. 303–307. *In* C. Royo et al. (ed.) Seminar on durum wheat improvement in the Mediterranean region: New challenges. 12–14 April 2000, CIHEAM-IAMZ, Zaragoza, Spain.

Paulsen, G.M. 1994. High temperature responses of crop plants. p. 365–389. *In* K.J. Boote (ed.) Physiology and determination of crop yield. ASA, CSSA, SSSA, Madison, WI.

Post, D.F., C. Mack, P.D. Camp, and A.S. Suliman. 1988. Mapping and characterization of the soils on the University of Arizona Maricopa Agricultural Center. p. 49–60. *In* 18th Proceedings of Hydrology and Water Resources of the Southwest, Arizona–Nevada Academy of Science.

Prasad, P.V.V., S.R. Pisipati, Z. Ristic, U. Bukovnik, and A.K. Fritz. 2008. Impact of nighttime temperature on physiology and growth of spring wheat. Crop Sci. 48:2372–2380. doi:10.2135/cropsci2007.12.0717

Rahman, M.A., J. Chikushi, S. Yoshida, and A.J.M.S. Karim. 2009. Growth and yield components of wheat genotypes exposed to high temperature stress under controlled environment. Bangladesh J. Agric. Res. 34(3):361–372.

Rocheford, T.R., D.J. Sammons, and P.S. Baenziger. 1988. Planting date in relation to yield and yield components of wheat in the middle Atlantic region. Agron. J. 80:30–34. doi:10.2134/agronj1988.00021962008000010007x

SAS Institute. 2009. The SAS system for Windows. V. 9.2. SAS Inst., Cary, NC.

Wall, G.W., B.A. Kimball, J.W. White, and M.J. Ottman. 2011. Gas exchange and water relation responses of spring wheat to full-season infrared warming. Glob. Change Biol. 17:2113–2133 .

Wardlaw, I.F., I.A. Dawson, P. Munibi, and T. Fewster. 1989. The tolerance of wheat to high temperatures during reproductive growth: I. Survey procedures and general response patterns. Aust. J. Agric. Res. 40:1–13. doi:10.1071/AR9890001

White, J.W., B.A. Kimball, G.W. Wall, and M.J. Ottman. 2011. Responses of time of anthesis and maturity to sowing dates and infrared warming in spring wheat. Field Crops Res.