

1 **Soybean sensitivity to simulated changes in rainfall, temperature, radiation and**
2 **irrigation at ambient and elevated carbon dioxide concentrations**

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24 ABSTRACT

25 We used a plant-growth simulation model to examine the influences of changes in
26 precipitation (P), air temperature (T) and solar radiation (R) singly and in combination on
27 soybean grown at ambient and elevated atmospheric CO₂ concentrations. Model
28 simulations examined: (i) effects of individual and combined changes in T, P and R on
29 soybean productivity; (ii) how are the effects expected to change with elevated CO₂
30 concentrations; and, (iii) how might irrigation alter the impacts? The model was
31 configured for a field site near Raleigh, NC (35.8 N, 78.6 W). Plant growth data from
32 open-top field chambers for elevated CO₂ experiments for 1999 and 2000 growing
33 seasons were used for model calibration. The model was modified and validated to
34 simulate soybean grown at ambient (371 μmol mol⁻¹) and elevated (708 μmol mol⁻¹)
35 CO₂ concentrations. The validated model was used to study responses to individual and
36 simultaneous changes in R, P and T with respect to observed conditions during 1999
37 and 2000 at ambient and elevated CO₂ concentrations under irrigated and non-irrigated
38 conditions. Single factor analysis results indicated that changes in P had the greatest
39 impact on water-stressed plants and irrigation modulated plant yield positively. R and T
40 effects can be non-linear and have positive or negative impact on plant growth
41 depending on soil moisture conditions. Twice-ambient CO₂ concentrations increased
42 simulated yields by 25% under +P conditions. Changing climatic variables
43 simultaneously, we found that: (i) increased P compensated for the negative effects of
44 increased R and T on yield; (ii) the interactive effects of R and T were modulated by the
45 magnitude and timing of P; and, (iii) relative impacts of increased R and T on yield
46 suppression were diminished with elevated CO₂. Yield responses were contingent upon

47 the level, timing and cumulative influence of R,T and P and their interactions during a
48 particular growing season, while elevated CO₂ generally enhanced yields and
49 ameliorated negative effects of increased R and T.

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52 Keywords: Agroecosystems, Climate change; Crop models; Precipitation, Solar
53 radiation, Soybean, Temperature.

54 **Introduction**

55 Recent climate projections have continued to predict increasing atmospheric CO₂
56 and water vapor levels along with changes in surface temperature and rainfall patterns
57 (IPCC 2007). Assessments suggest that changes in North American climate may
58 increase agricultural yields in colder environments, but present major challenges for
59 crops grown in warmer climates or with limited water resources (Hatfield 2008, IPCC
60 2007, Working Group II Report pg 15, Iglesias et al. 1996). These assessments are
61 based on field experiments that have analyzed effects of climate change on agricultural
62 systems, usually using single factor approaches (Allen et al. 1987, Lawlor & Mitchell
63 1991, Rosenzweig & Hillel 1998, Jablonski et al. 2002, Council for Agricultural Science
64 and Technology 2004, Allen et al. 2004, Pritchard 2005). Models such as CSM-
65 CROPGRO-Soybean¹ and CSM-CERES-Maize¹ (Jones et al. 2003, 2004) and their
66 predecessors have been used to project climate change effects on crop growth and
67 yield (Wolfe & Erickson 1993, Pickering et al. 1993, 1995, Easterling et al. 1993,
68 Mearns et al. 1992, 1997, Hoogenboom 2000, National Research Council 2005, Mera et
69 al. 2006). These models can also be used to explore multi-factor changes in
70 environmental parameters.

71 Over the years, models have been used to study the impacts of precipitation,
72 temperature and solar radiation changes on crop performance (Wolf & van Diepen
73 1995, Carlson & Bruce 1996, Hansen et al. 1996, Brown & Rosenberg 1997, Lal et al.
74 1998, Hansen et al. 1999, Southworth et al. 2000, Wang et al. 2001, Magrín et al. 2002,
75 Wolf 2002, Mall et al. 2004, Mera et al. 2006). Generally, precipitation alterations
76 translate into significant yield changes. The CROPGRO-Soybean model has been used

¹ CSM-CROPGRO and CSM-CERES are acronyms for Cropping System Model

77 for site specific evaluations at several locations, such as Missouri (Wang et al. 2001),
78 Hawaii (Ogoshi et al. 1998) and North Carolina (Boote et al. 1997). A multi-year, multi-
79 state compilation of studies by Jones et al. (2004) concluded that CSM-CROPGRO-
80 Soybean could be used to simulate a variety of environmental conditions including
81 drought response of soybean cultivars.

82 A number of climate-change impact studies with CROPGRO-Soybean have
83 probed the effects of enhanced CO₂ concentration on plant growth. For example,
84 studies by Boote et al. (1997, 2002a,b), Hoogenboom (2004), and Alagarswamy et al.
85 (2006) compared CROPGRO-Soybean simulated leaf photosynthesis to published data
86 by Harley et al. (1985), Sims et al. (1998) and Griffin and Luo (1999). The studies
87 showed that the crop model can be used to simulate photosynthetic processes under
88 elevated CO₂ conditions. Alagarswamy et al. (2006) found that the model's default
89 photosynthesis equations were capable of predicting observed effects of elevated CO₂
90 on soybean photosynthesis and productivity. Therefore, the CSM-CROPGRO-Soybean
91 model, which is part of the Decision Support System for Agrotechnology Transfer
92 (DSSAT) Version 4.0 (Jones et al. 2003, Hoogenboom et al. 2004), was selected for
93 use in this study.

94 Our objectives were to: (i) calibrate CSM-CROPGRO-Soybean to simulate
95 soybean growth in open-top field chambers (OTCs) under ambient CO₂ concentrations;
96 (ii) verify that the model could accurately simulate responses to enhanced CO₂
97 concentrations in these chambers; and (iii) evaluate influences of changes in
98 precipitation (P), air temperature (T) and radiation (R) singly and in combination on
99 soybean growth and yield at ambient and elevated CO₂ concentrations. Simulations

100 were designed to address three questions: (i) what is the effect of individual and
101 simultaneous changes in T, P and R on crop productivity; (ii) how is the effect expected
102 to change with elevated CO₂; and (iii) how might irrigation change the impacts?
103

104 **Methodology**

105 Field experiments are useful for validating model performance. Previous studies
106 have shown that results can be highly variable due to the genotypes used, differences
107 in experimental protocols and interannual variability in environmental conditions
108 (Kimball 1983, Fiscus et al. 2001, Ainsworth et al. 2002, Kubiske et al. 2006). Variability
109 in field study results may also arise from interactions between environmental variables
110 not previously recognized as pertinent (Jablonski 2002, Fiscus et al. 2001). To minimize
111 analysis variance, the crop model was first calibrated using field-grown soybean
112 [*Glycine max* (L.) Merr.] data at ambient atmospheric CO₂ levels (Booker et al. 2005).
113 The calibrated model was then tested against field data obtained under enhanced CO₂
114 concentrations. Following calibration and testing, simulations utilizing modified climate
115 data (R, P and T) were made using a factorial design at ambient and elevated CO₂
116 levels and under irrigated and non-irrigated conditions. Effect of irrigation was only
117 evaluated in model simulations, as all field treatments were irrigated to minimize plant
118 water stress (Booker et al. 2005).

119

120 **2.1 Crop Model**

121 CSM-CROPGRO-Soybean (Jones et al. 2003) is part of the DSSAT suite of crop
122 models (Hoogenboom et al. 2004). CSM-CROPGRO-Soybean is a process-oriented

123 model which simulates soybean growth and development, soil and plant water
124 dynamics, and carbon and nitrogen dynamics (Boote et al. 1998). Model inputs include
125 weather, soil, cultivar and crop management data. Crop development in the model is
126 differentially sensitive to temperature, photoperiod, and water and nitrogen stresses
127 during various developmental stages, and is expressed as physiological days per
128 calendar day (PD/day). The model simulates changes in photosynthesis and
129 evapotranspiration caused by elevated CO₂ (photosynthesis equations are contained in
130 Alagarswamy et al. 2006; Tsuji et al. 1998)

131

132 **2.2 Open-Top Field Chamber Measurements**

133 To configure CSM-CROPGRO-Soybean, data from an experiment by Booker et
134 al. (2005) comparing field-grown soybean growth and yield under ambient and twice-
135 ambient CO₂ levels was used. The experiment was conducted 5 km south of Raleigh,
136 NC (35.8 N, 78.6 W) using open-top chambers (OTCs) and the soybean cultivar Essex.
137 Essex is a determinate, early-maturity group V cultivar. Experimental data included
138 anthesis, physiological maturity and harvest dates as well as pod, stem and seed
139 masses. Elevated CO₂ treatments were administered 24 h d⁻¹. In combination with the
140 CO₂ treatments, plants were treated with either charcoal-filtered air (clean air
141 conditions) or non-filtered air with added ozone (O₃). Because CSM-CROPGRO-
142 Soybean assumes ambient O₃ levels and does not explicitly simulate O₃ effects on
143 soybean growth, only data collected from ambient and elevated CO₂ treatments with
144 charcoal-filtered air were used for model calibration and testing, realizing that growth
145 was likely enhanced by the absence of O₃ (Heagle 1989, Morgan et al. 2003).

146 Soil was an Appling sandy loam (Fine, kaolinitic, thermic Typic Kanhapludults).
147 Fertilizer was applied according to soil test recommendations with 132.4 kg K ha⁻¹ on 18
148 May 1999 and on 17 May 2000. Seeds were treated with a commercial *Bradyrhizobium*
149 preparation and planted on 24 May 1999 and 31 May 2000. Row spacing was 1 m and
150 plant spacing was 5.5 cm (18 plants m⁻²) and 7.7 cm (13 plants m⁻²) in 1999 and 2000,
151 respectively. Weather data were recorded on-site (Booker et al. 2005) and at a nearby
152 weather station.

153 Plants were irrigated as required to prevent visible signs of water stress. Total
154 irrigation was 41.4 cm in 1999 and 6.7 cm in 2000. The field site received about 65 cm
155 of rainfall each year. However, in 1999, 71% (46 cm) of the precipitation occurred in
156 September (Booker et al. 2005, Table 1). Plots were sprayed to control spider mites
157 and insects on 2 August 1999 and 20 June, 28 June, 21 July and 1 September 2000
158 (Booker et al. 2005).

159 In 1999, midseason above-ground biomass samples were taken at 98 to 102
160 days after planting (DAP). At 162 to 164 DAP, in 1999, two 80-cm row sections in each
161 of two rows were harvested for yield measurements. In 2000, two 100-cm row sections
162 in each of two rows were harvested for yield at 146 to 149 DAP. As with 1999, the dry
163 mass of leaves, stems, branches, pods and seeds was measured.

164 Using soil, weather, irrigation, and management data specified for the 1999 and
165 2000 ambient CO₂ treatments, CSM-CROPGRO-Soybean parameters were initialized.
166 Simulated results were then compared to observed treatment values for anthesis and
167 physiological maturity dates and stem, pod and seed mass at harvest. Two model
168 parameters, soil fertility factor (SLPF) and maximum leaf photosynthetic rate (LFMAX),

169 were adjusted to calibrate the model to the observed treatment values. After the model
 170 had been calibrated to data from ambient CO₂ treatments, simulated responses to
 171 elevated CO₂ were compared to observed treatment data from the enhanced CO₂
 172 treatments.

173

174 **2.3 Experimental Analysis**

175 After calibration and testing against enhanced CO₂ treatment observations,
 176 studies were conducted to evaluate how changes in P, T and R could affect seed yield.
 177 To assess individual changes in climatic conditions, daily meteorological observations
 178 for both years were modified as follows: P values were set to 25%, 50%, 75%, 125%
 179 and 150% of observed; R values were 25%, 50%, 75% and 125% of observed; and T
 180 values were ± 1 °C, ± 2 °C, ± 3 °C, and ± 4 °C of observed. These changes were
 181 applied to both ambient and enhanced CO₂ treatments. In these simulations, plots were
 182 assumed either to have been rain fed (no irrigation) or to have been irrigated according
 183 to the schedules used in the 1999 and 2000 field experiments.

184 To examine the impact of simultaneous changes to weather variables and their
 185 interactions, a procedure called factor separation analysis was employed (Stein and
 186 Alpert, 1993). The direct effects of variables and their interactions were calculated as
 187 follows:

$$188 \quad E_0 = (-R-P-T) \quad (1a)$$

$$189 \quad E_R = (+R-P-T) - E_0 \quad (1b)$$

$$190 \quad E_P = (-R+P-T) - E_0 \quad (1c)$$

$$191 \quad E_T = (-R-P+T) - E_0 \quad (1d)$$

$$192 \quad E_{RP} = (+R+P-T) - E_R - E_P - E_0 \quad (1e)$$

$$193 \quad E_{RT} = (+R-P+T) - E_R - E_T - E_0 \quad (1f)$$

$$194 \quad E_{PT} = (-R+P+T) - E_P - E_T - E_0 \quad (1g)$$

$$195 \quad E_{RPT} = (+R+P+T) - E_{RP} - E_{RT} - E_{PT} - E_R - E_P - E_T - E_0 \quad (1h)$$

196

197 Daily meteorological observations were modified as follows: $\pm 50\%$ of observed
 198 P, $\pm 25\%$ of observed R, and $\pm 2^\circ\text{C}$ of observed T. Parameter ranges were based on
 199 summary projections from climate model results and analysis of past regional climate
 200 data for seasonal variations (Mera et al. 2006). Increases and decreases in R, P and T
 201 used in the equations above are defined in Table 2. Terms on the left hand side of the
 202 equation represent individual impacts or their interactions and are defined as follows: E_0
 203 = background effect without R, P or T effects (all are set to lowest value); E_R , E_P and E_T
 204 = individual impacts or variable sensitivity; E_{RP} , E_{RT} and E_{PT} = double interactions due to
 205 simultaneous increases in the variables; E_{RPT} = triple interactions between R, P and T.
 206 This procedure provides estimates of the influences of the various weather variables on
 207 yield responses and quantifies responses attributable to interactions between various
 208 weather variables (Stein and Alpert 1993),

209

210 **3. Results**

211 **3.1 Environmental Conditions**

212 Climatic conditions during the two growing seasons included a generally hot and
 213 dry summer in 1999 and a cooler, wetter summer in 2000, except for September, which
 214 was cooler and wetter in 1999 than in 2000 (Table 1). The weather conditions utilized in

215 this experiment were retrieved from a nearby weather station (Raleigh, NC) that had
216 complete daily data for the variables required. Figures 1a and 1b show the variation in
217 individual climatic variables throughout the growing season for 1999 and 2000,
218 respectively. The mean CO₂ concentration in the 1999 ambient and elevated CO₂
219 treatments was 373 and 699 $\mu\text{mol mol}^{-1}$ (12 h daily average, 08.00 – 20.00 h EST),
220 respectively. In 2000, the mean ambient CO₂ concentration was 369 and enhanced
221 concentration was 717 $\mu\text{mol mol}^{-1}$.

222

223 **3.2 Model Validation**

224 CSM-CROPGRO-Soybean was calibrated to simulate growth and yield in OTCs
225 under ambient CO₂ conditions using data for the 1999 and 2000 seasons. It should be
226 noted that CSM-CROPGRO-Soybean is primarily designed to simulate soybean growth
227 and development under normal field conditions. Therefore, for this study, model
228 calibration was required to compensate for differences in management and
229 microclimatic factors between OTCs and normal field conditions. Chamber plots are
230 typically highly managed. They have warmer daytime temperatures as compared to the
231 field. There is increased light interception by plants along the chamber perimeter but
232 decreased daily solar radiation levels, and air supplied to the chamber is charcoal-
233 filtered (Booker et al. 2005). The model's soil fertility factor (SLPF) is normally used to
234 adjust crop photosynthesis relative to soil nutrient differences between fields
235 (Hoogenboom et al. 2004). Initial calibration was done by adjusting SLPF and
236 maximum leaf photosynthetic rate (LFMAX) at 30 °C, 371 $\mu\text{mol CO}_2 \text{ mol}^{-1}$ and high light
237 levels to fit simulated yields to measured ambient CO₂ treatment yields. Calibration

238 resulted in a LFMAX value of 1.25 for both seasons and SLPF values of 1.4 for 1999
239 and 1.27 for 2000. Results suggest the model is not over-fitted and that simulated seed
240 mass for both seasons was within the margin of error for the observations (Fig. 2).

241 Once the model had been calibrated for ambient conditions in the two seasons,
242 enhanced CO₂ treatments were simulated. The model performed well and estimated
243 final seed, pod and stem mass within 1% for both years.

244

245 **3.3 Impact of Individual Climate Variable Changes**

246 Figure 3 shows the impact of R changes for the two years under ambient and
247 enhanced CO₂ conditions (with and without irrigation). Yield changes varied depending
248 on the season (1999, 2000), CO₂ treatment and irrigation. Responses to increased R
249 were similar for ambient and enhanced CO₂ levels for a given season and irrigation
250 practice. The highest simulated yield (~10,000 kg ha⁻¹) occurred at 125% of the
251 observed R level for the 1999 enhanced CO₂-irrigated treatment. Under ambient CO₂
252 conditions, the highest simulated yield (~8,000 kg ha⁻¹) was also obtained for the 1999
253 irrigated treatment at 125% of the observed R level. Simulated yields increased steadily
254 as R increased from 25% to 125% of observed in both years for ambient and enhanced
255 CO₂ levels under irrigated conditions. However, under non-irrigated conditions,
256 responses to increasing R were different for the two years. For the 2000 season,
257 increasing R from 25% to 100% resulted in higher simulated yields, with no further
258 increase at 125% of the observed R. In 1999, simulated yield increased as R was
259 raised from 25% to 75% of observed, but declined at higher levels. Since there were
260 long periods with limited rainfall in 1999 but not in 2000 (Fig. 1), this difference may be

261 indicative of the impact of increased R leading to increased water loss through
262 evapotranspiration, causing greater crop water stress, as noted below.

263 The importance of water, from precipitation and irrigation, was apparent for
264 experiments with different levels of P (Fig. 4). Yield in the irrigated 1999 ambient CO₂
265 simulation was ~6900 kg ha⁻¹ for all P values. Yield in the irrigated 1999 elevated CO₂
266 simulation was ~8200 kg ha⁻¹ for all simulations. Non-irrigated simulations for 1999
267 showed increasing yields with higher P in an otherwise dry season. Yield differences
268 between the ambient and enhanced CO₂ simulations ranged from ~500 kg ha⁻¹ at 25%
269 of observed P to ~1500 kg ha⁻¹ at 150% of observed P.

270 The 2000 growing season was wetter than 1999 and less irrigation was applied.
271 For irrigated simulations, yields were similar for treatments at 50% of observed P and
272 above (~6200 kg ha⁻¹ for ambient CO₂ treatments and ~7900 kg ha⁻¹ for enhanced CO₂
273 treatments), but decreases in P below 50% of observed P resulted in decreased yield.
274 Non-irrigated treatments showed a linear rise in yields from 25% to 75% of observed P,
275 with no increases thereafter (simulated yields ~7900 kg ha⁻¹ for enhanced CO₂ and
276 ~6200 kg ha⁻¹ for ambient CO₂ at 75% of observed P and above). Based on these
277 results, irrigation applied in 2000 did not affect simulated yields to the extent it had in
278 the 1999 season and even a 25% reduction in rainfall (75% P) would not have
279 significantly decreased yields. This is especially true for enhanced CO₂, where yield
280 loss was negligible. Thus, soil moisture content during the growing season strongly
281 modulated the impact of atmospheric CO₂ concentration on yield (cf. Nemani et al.
282 2002, Niyogi & Xue 2006).

283 Figure 5 shows the impact of T on the different treatments. The 1999 enhanced
284 and ambient CO₂ treatments with irrigation had the highest simulated yields (~8200 kg
285 ha⁻¹ and ~6900 kg ha⁻¹, respectively) at a seasonal average T of 23 to 24 °C. Simulated
286 yields decreased as T increased above this range. Soybean yield and seed quality
287 typically decline when mean daily T exceeds an optimum of about 26 °C (Allen & Boote
288 2000, Prasad et al. 2005). In the 1999 non-irrigated simulations, yield peaked at 21 °C
289 for the elevated and ambient CO₂ treatments (6600 kg ha⁻¹ and 4700 kg ha⁻¹,
290 respectively). Maximum yield likely occurred at a lower seasonal T in non-irrigated
291 plants because simulated cooler T extended the plant development period and duration
292 for seed fill (Fig. 6) while water stress would also be less. However, yield is not only
293 sensitive to changes in mean T but also to the timing of T variations. For example, in
294 2000 when a seasonal average T of 19 °C delayed plant development, including start of
295 seed fill (Fig. 6), an October freeze (Fig. 1) occurred prior to simulated physiological
296 maturity, killing the plant, ending seed growth and suppressing yield (Fig. 5). If T had
297 been higher prior to this freeze, the plants would have completed seed growth and the
298 freeze would have had no impact on yield. This highlights one inherent uncertainty in
299 projecting impacts on yield due to changes in average T.

300 Yields were more adversely affected by increasing T under 1999 non-irrigated
301 conditions than in any of the well-watered simulations. Simulated yields under irrigated
302 conditions generally decreased by 4 to 5% for every 1 degree rise in T above optimum
303 for ambient CO₂ conditions and 3 to 4% for enhanced CO₂ conditions. For non-irrigated
304 conditions, ambient and elevated CO₂-simulated yields decreased from their optimums
305 with increased T at an initial rate of 11% and a final rate of 6% at the warmest

306 conditions. Irrigated and non-irrigated 2000 simulations at ambient and enhanced CO₂
307 levels exhibited similar nonlinear yield responses to T changes (Fig. 5).

308 Results also showed, at both ambient and enhanced CO₂ in 2000, there was little
309 difference in the response to T changes for irrigated and non-irrigated treatments. This
310 again illustrates the important interaction between CO₂ concentration and water (from
311 rainfall and irrigation) during the growing season.

312

313 **3.4 Simultaneous Climate Variable Changes**

314 Figure 7 shows the effect of the weather variables and their interactions on yield.
315 Direct effects of individual variables are identified as E_R , E_T and E_P . Effects related to
316 the interaction of two variables (e.g. R and T varying simultaneously) are identified as
317 E_{RT} , E_{PT} and E_{RP} . The combined effect of all three variables on yield is identified as
318 E_{RPT} (cf. Eq 1). Table 3 (1999 season) and Table 4 (2000 season) list the simulated
319 yields used in the factor separation analysis. The tables also show relative changes in
320 yields compared with baseline conditions as well as relative responses at elevated
321 compared with ambient CO₂ concentrations ($e[\text{CO}_2] / a[\text{CO}_2]$).

322 Factor separation analysis showed that increased R (E_R) positively contributed to
323 yield under irrigated conditions at both CO₂ levels for the two years (Tables 3 and 4,
324 Fig. 7). For non-irrigated (increased water stress) conditions, there was a negative
325 effect of +R on yield. If soil moisture levels were adequate, an increase in R under
326 enhanced CO₂ conditions increased yield more than the same R increase did under
327 ambient CO₂ conditions (Tables 3 and 4, Fig. 7).

328 When the direct effect of increased P (E_P) on yield was analyzed, the impact of
329 water stress was clear. As expected, the impact was notable in the absence of
330 irrigation in a dry year (1999) (Table 3, Fig. 7A). In 2000, increased P had no impact on
331 yield, as there was sufficient soil moisture to meet crop evapotranspiration requirements
332 (Table 4, Fig. 7B). An increase in T (E_T) alone negatively affected yield, especially
333 when the crop experienced water stress.

334 Under irrigated conditions in both 1999 and 2000, there was no interaction
335 between increased T and P (E_{PT}), not surprising since increasing P (E_P) had no effect
336 on yield (Fig. 7). Non-irrigated simulations for both years showed a positive E_{PT} effect
337 on yield at both CO_2 concentrations, with 1999 being markedly higher, demonstrating
338 the significance of this interaction when water stress was present. While the increase in
339 P stimulated yield in dry conditions, the negative effect of higher T dampened the
340 response, and yields were less than those observed with higher P alone (Tables 3 and
341 4, Fig. 7). However, simulated yield increases in the non-irrigated $-R+P+T$
342 combination, compared with the base combination ($-R-P-T$), were greater than would be
343 calculated by summing the changes in the individual variable responses [$(-R-P+T) + (-$
344 $R+P-T)$], as indicated by E_{PT} in Table 3 and Figure 7A. The E_{PT} differential yield
345 represents the P x T interaction that occurred when both variables were simultaneously
346 increased in the simulation and illustrated how increased P and T interacted
347 synergistically to affect yield. In this case, the positive effect of increased P on
348 promoting yield more than compensated for the yield-suppressing effect of increased T.
349 In 2000, the small negative effects of increased T were negated by increased P when
350 the two factors were examined simultaneously (Table 4, Fig. 7B). Again, this

351 interpretation differed from one that might be reached after examining the effects of the
352 individual factor simulations.

353 The R x P interaction (E_{RP}) also had a mostly positive impact on yield, with a
354 much greater contribution under non-irrigated conditions (Tables 3 and 4, Fig. 7). The
355 inhibitory effect of increased R levels in non-irrigated plants was more than negated by
356 increased P, and yields were substantially improved. In 1999, increased P had little
357 effect on E_{RP} for irrigated plants, whereas in 2000, the E_{RP} combination increased seed
358 yield by about 1500 and 1300 kg ha⁻¹ at ambient and elevated CO₂ concentrations,
359 respectively (Tables 3 and 4, Fig. 7).

360 The impact of the R x T interaction (E_{RT}) was negative for most simulations,
361 although in 1999 the response to E_{RT} in non-irrigated plants was less than the sum of
362 the individual negative effects of E_R and E_T , which resulted in a positive differential yield
363 for this parameter combination (Table 3, Fig. 7). In 2000, there was a strong negative
364 synergistic R x T interaction in all treatments (Table 4, Fig. 7). These responses were
365 associated with increased water stress during a critical stage for pod formation and
366 seed growth in August. During the period August 8 to August 31 (69 to 92 days after
367 planting), evapotranspiration (ET) was 31, 48, 95, and 100% of potential ET,
368 respectively, for simulations in which both R and T, R alone, T alone, or neither R or T
369 was increased at ambient CO₂. Under enhanced CO₂, ET was 31, 50, 98, and 100% of
370 potential ET for these conditions. Canopy biomass accumulated faster during vegetative
371 growth period, but pod initiation was severely curtailed by the combination of elevated R
372 and T in conjunction with low soil moisture content in early August 2000 (Fig. 8). The
373 confluence of R, T and P effects that impacted yields differently in 1999 versus 2000

374 further illustrated how the magnitude and timing of weather patterns in any particular
375 growing season can have major influences on yield, as was noted above when cool
376 seasonal temperature and an early freeze lowered yield.

377 The triple interaction E_{RTP} showed that T can, sometimes antagonistically, modify
378 the R x P interaction (E_{RP}) in all treatments. As with the E_{RP} and E_{RT} interactions, water
379 stress played a significant role in the way climatic factors influenced seed yield. There
380 were marginally positive contributions from the prescribed climatic changes (E_{RTP}) for
381 the irrigated 1999 simulations (Table 3, Fig. 7A). In contrast, when water stress was a
382 dominant factor, there were marked negative contributions of the prescribed climatic
383 changes for that same year as the combined effect of increased R and T suppressed
384 the positive impact of increased P, and differential yield declined. In 2000, the R x T x P
385 interaction (E_{RPT}) relieved the inhibitory effect of low soil moisture content during the
386 early stage of pod formation and differential yields were strongly positive (Table 4, Fig.
387 7B).

388 The E_{RTP} interaction effects for all simulations varied significantly from 1999 to
389 2000. In 2000, the differential yield response to E_{RTP} was positive as a result of the
390 more favorable rainfall pattern. These interpretations were evidenced by the simulated
391 percentages of ET to potential ET. For the simulations in which R, P and T were
392 increased simultaneously under ambient CO_2 , ET averaged 94% of potential in 2000
393 and 64% of potential in 1999 from August 8 to August 31 (pod set and early seed
394 growth stages). Simulated canopy T averaged 2 degrees higher in 1999 during the
395 same time period (data not shown).

396

397 **3.5 Elevated CO₂ Responses**

398 Simulated soybean yield responses at elevated CO₂ were enhanced by 18 to
399 27% compared with ambient CO₂ concentrations under irrigated and +P scenarios,
400 depending on the influences of +R and +T (Tables 3 and 4). This range of
401 enhancement ratios was similar to that observed in a meta-analysis of elevated CO₂
402 experiments with soybean (Ainsworth et al. 2002), but lower than that found in other
403 studies (Lal et al. 1999, Allen & Boote 2000). The negative effects of increased R and
404 T, usually in combination with –P, were greater with ambient than elevated CO₂
405 concentrations, as indicated by increased $e[\text{CO}_2] / a[\text{CO}_2]$ ratios for these parameter
406 combinations (Tables 3 and 4). This response was likely related to water stress rather
407 than +T *per se* as the CO₂ enhancement ratios were little affected by +T under well-
408 watered simulations (Tables 3 and 4). Previous studies have found that water stress
409 decreased soybean yields at ambient CO₂ to a greater extent than at elevated CO₂
410 concentrations (Allen & Boote 2000), possibly due to increased water use efficiency,
411 root production and N₂-fixation capacity (Booker et al. 2004 De Luis et al. 1999). In
412 regard to whether yield was affected differently at elevated versus ambient CO₂
413 concentrations in the various weather combinations, comparisons of relative changes
414 from baseline conditions in the various weather scenarios at elevated and ambient CO₂
415 indicated little difference among responses except that elevated CO₂ diminished the
416 negative impact of +R and +T on yield suppression by about 10% (Tables 3 and 4). In
417 contrast, the stimulatory effect of elevated CO₂ on yield could be diminished if P
418 increased, as in 1999 when the yield enhancement with elevated CO₂ was 10% less
419 than that with ambient CO₂ and +P in non-irrigated plants (Table 3).

420

421 **Conclusions**

422 The CSM-CROPGRO-Soybean model was calibrated and tested using data from
423 an OTC soybean experiment (1999 and 2000) in which plants were grown at ambient
424 and elevated CO₂ concentrations. To account for alterations in light interception around
425 the plot perimeter and inside the chamber, reduced O₃ concentrations and high
426 management levels associated with OTCs, two model parameters, maximum leaf
427 photosynthetic rate (LFMAX) and the soil fertility factor (SLPF), were adjusted. Using
428 ambient CO₂ conditions only, calibration results produced a LFMAX value of 1.25 for
429 both years and a SLPF value of 1.4 for 1999 and 1.27 for 2000. The calibrated model
430 was then tested for elevated CO₂ conditions, where the simulated yields were
431 comparable to measured yields. Based on these results, the modified CSM-
432 CROPGRO-Soybean model was used to simulate crop growth at different CO₂ levels.

433 Simulations to evaluate the influence of changes in R on soybean growth and
434 yield showed a nonlinear response for most scenarios. Results were growing-season
435 dependent, with soil moisture content during the growing season being a primary factor.
436 Maximum non-irrigated simulated yields for ambient and elevated CO₂ conditions in
437 1999 occurred at 75% of observed R. In 2000, non-irrigated maximum yield occurred at
438 100% for ambient CO₂ conditions and 125% for enhanced CO₂ conditions. Irrigated
439 simulated yields, at both ambient and elevated CO₂ levels, increased as R increased.
440 All enhanced CO₂ simulations, irrigated and non-irrigated, had higher yields than
441 equivalent ambient CO₂ simulations. Based on these results, soybean yield was directly
442 related to R at ambient and enhanced CO₂ levels when water stress was not a factor.

443 As expected, results from the sensitivity study showed P changes were not as
444 dominant when irrigation was applied (1999) or when P met or exceeded plant-water
445 requirements during the growing season (2000). Past studies (e.g. Morrison 1993,
446 Drake et al. 1997) have also shown that, across CO₂ concentrations, dry matter
447 accumulation was dependent on available water. The factor analysis showed that
448 increasing T negatively influenced yield. This is in agreement with individual sensitivity
449 tests performed by Mera et al. (2006). Controlled environment and field studies have
450 also found that soybean yield increases in response to enhanced CO₂ levels can be
451 negatively offset by higher T, but a T x elevated CO₂ interaction has generally not been
452 observed (Baker et al. 1989, Morrison,1993, Baker et al. 1993, Allen & Boote 2000, Mall
453 et al. 2004, Prasad et al. 2005).

454 Previous research has found that soybean yield increases between current
455 ambient and twice-ambient CO₂ concentrations (Ainsworth et al. 2002, Prasad et al.,
456 2005). Simulations in this study show that R, P and T and interactions among these
457 factors influence the extent of the yield increases associated with increased CO₂ that
458 might be realized. Inadequate P, supra-optimal T and low R levels diminish yield gain
459 with elevated CO₂ while high R and adequate water to meet plant requirements
460 maximize yield gain. With climate predictions indicating T and P patterns that may
461 result in increased plant water stress, it is unclear how much of the anticipated yield
462 gain from CO₂ increases may occur. Adjustments in soybean production practices,
463 however, may mitigate some of the negative effects associated with climate change.
464 Since water is the dominant factor, irrigation practices would likely be employed while
465 conjunctively addressing economic considerations attached to their effectiveness. Crop

466 growth models could be used in conjunction with weather forecasts to possibly foresee
467 potential combinations of R, T and P likely to have strong impacts on yield, such as for
468 pod development in 2000, so that supplemental irrigation could be employed to mitigate
469 potential losses. Development and use of drought- and heat-tolerant cultivars could be
470 beneficial, as could utilization of cultivars with different development patterns. In
471 addition, changes in planting date could be made to minimize stresses during important
472 development stages such as flowering and seed fill. Although soybean sensitivity to
473 climatic factors can be shown, production practices and economic considerations need
474 to be included to determine the impact of climate change on soybean production.

475

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720

721 Table 1. Average seasonal and monthly weather conditions (from weather station) and
 722 CO₂ concentrations (Booker et al. 2005). CO₂ concentrations are 12 h d⁻¹ (08.00–
 723 20.00 h EST) averages.

724

Parameter	Year	June	July	Aug.	Sept.	Oct. 1-16	Season
Temperature, °C	1999	24	27	27	21	18	24
	2000	25	24	25	23	17	23
Precipitation, mm	1999	52	55	80	461	8	656
	2000	175	121	140	257	0	693
Radiation (MJ m ⁻²)	1999	19	21	20	14	12	18
	2000	22	19	20	14	14	18
[CO ₂], μmol mol ⁻¹							
Ambient	1999	380	366	370	372	386	373
Enhanced	1999	659	703	737	689	688	699
Ambient	2000	368	361	365	373	376	369
Enhanced	2000	700	764	730	714	686	717

725

726 Table 2. Environmental factor combinations in modeled multiple interaction simulations. Solar radiation
 727 (R), precipitation (P) and temperature (T) values in simulations were relative to those observed daily in
 728 the 1999 and 2000 soybean field experiment (Booker et al. 2005).

729

Variable conditions relative to observed			
Parameter combination	Radiation (R)	Precipitation (P)	Temperature (T)
-R-P-T	75%	50%	-2 °C
+R-P-T	125%	50%	-2 °C
-R+P-T	75%	150%	-2 °C
-R-P+T	75%	50%	+2 °C
+R+P-T	125%	150%	-2 °C
+R-P+T	125%	50%	+2 °C
-R+P+T	75%	150%	+2 °C
+R+P+T	125%	150%	+2 °C

730

- 731 Table 3. Factor separation simulation yields for each parameter combination (see Table 2) for treatments at ambient ($a[\text{CO}_2]$) and elevated CO_2
- 732 ($e[\text{CO}_2]$) concentrations in 1999 (irrigated and non-irrigated). Values in parentheses indicate the relative effect of each parameter combination on
- 733 yield compared with baseline conditions (-R-P-T). Enhancement ratios with elevated CO_2 ($e[\text{CO}_2]/a[\text{CO}_2]$) for yield and relative (Rel.) yield change
- 734 from baseline conditions in irrigated and non-irrigated scenarios are also shown.

Parameter combination	Simulated yields for parameter combinations (kg ha^{-1})									
	$a[\text{CO}_2]$ irrigated	$a[\text{CO}_2]$ non-irrigated	$e[\text{CO}_2]$ irrigated	$e[\text{CO}_2]$ non-irrigated	$e[\text{CO}_2]/a[\text{CO}_2]$ irrigated	$e[\text{CO}_2]/a[\text{CO}_2]$ non-irrigated	$e[\text{CO}_2]/a[\text{CO}_2]$ irrigated	$e[\text{CO}_2]/a[\text{CO}_2]$ non-irrigated	Rel. $e[\text{CO}_2]$ / irrigated	Rel. $e[\text{CO}_2]$ / non-irrigated
+R+P+T	7599 (1.44)	3457 (0.95)	9302 (1.49)	5026 (0.98)	1.22	1.45	1.03	1.03	1.03	1.03
+R+P-T	8090 (1.53)	5070 (1.39)	9686 (1.55)	7036 (1.38)	1.20	1.39	1.01	1.01	0.99	0.99
+R-P-T	8236 (1.56)	1953 (0.54)	9729 (1.55)	2741 (0.54)	1.18	1.40	1.00	1.00	1.00	1.00
+R-P+T	7243 (1.37)	1375 (0.38)	9207 (1.47)	2126 (0.42)	1.27	1.55	1.07	1.07	1.10	1.10
-R+P+T	4927 (0.93)	4338 (1.19)	5940 (0.95)	5531 (1.08)	1.20	1.28	1.02	1.02	0.91	0.91
-R+P-T	5294 (1.00)	5139 (1.41)	6259 (1.00)	6308 (1.24)	1.18	1.23	1.00	1.00	0.88	0.88
-R-P+T	4927 (0.93)	2266 (0.62)	5940 (0.95)	3391 (0.66)	1.20	1.50	1.02	1.02	1.06	1.06
-R-P-T	5294 (1.00)	3642 (1.00)	6259 (1.00)	5103 (1.00)	1.18	1.40	1.00	1.00	1.00	1.00

735

- 736 Table 4. Factor separation simulation yields for each parameter combination (see Table 2) for treatments at ambient ($a[\text{CO}_2]$) and elevated CO_2
- 737 ($e[\text{CO}_2]$) concentrations in 2000 (irrigated and non-irrigated). Values in parentheses indicate the relative effect of each parameter combination on
- 738 yield compared with baseline conditions (-R-P-T). Enhancement ratios with elevated CO_2 ($e[\text{CO}_2]/a[\text{CO}_2]$) for yield and relative (Rel.) yield change
- 739 from baseline conditions in irrigated and non-irrigated scenarios are also shown.

Parameter combination	Simulated yields for parameter combinations (kg ha^{-1})											
	$a[\text{CO}_2]$ irrigated	$a[\text{CO}_2]$ non-irrigated	$e[\text{CO}_2]$ irrigated	$e[\text{CO}_2]$ non-irrigated	$a[\text{CO}_2]$ irrigated	$a[\text{CO}_2]$ non-irrigated	$e[\text{CO}_2]$ irrigated	$e[\text{CO}_2]$ non-irrigated	$e[\text{CO}_2]/a[\text{CO}_2]$ irrigated	$e[\text{CO}_2]/a[\text{CO}_2]$ non-irrigated	Rel. $e[\text{CO}_2]$ irrigated	Rel. $e[\text{CO}_2]$ non-irrigated
+R+P+T	6935 (1.45)	6610 (1.38)	8833 (1.48)	8641 (1.44)	8833 (1.48)	8641 (1.44)	1.27	1.31	1.02	1.02	1.00	1.04
+R+P-T	7273 (1.52)	7268 (1.52)	9132 (1.53)	9132 (1.53)	9132 (1.53)	9132 (1.53)	1.26	1.26	1.00	1.00	1.00	1.00
+R-P-T	5780 (1.21)	3812 (0.80)	7845 (1.31)	5565 (0.93)	7845 (1.31)	5565 (0.93)	1.36	1.46	1.08	1.08	1.08	1.17
+R-P+T	3782 (0.79)	1304 (0.27)	5436 (0.91)	1798 (0.30)	5436 (0.91)	1798 (0.30)	1.44	1.38	1.15	1.15	1.10	1.10
-R+P+T	4546 (0.95)	4546 (0.95)	5780 (0.97)	5780 (0.97)	5780 (0.97)	5780 (0.97)	1.27	1.27	1.02	1.02	1.02	1.02
-R+P-T	4783 (1.00)	4783 (1.00)	5986 (1.00)	5986 (1.00)	5986 (1.00)	5986 (1.00)	1.25	1.25	1.00	1.00	1.00	1.00
-R-P+T	4546 (0.95)	4255 (0.89)	5780 (0.97)	5744 (0.96)	5780 (0.97)	5744 (0.96)	1.27	1.35	1.02	1.02	1.02	1.08
-R-P-T	4783 (1.00)	4783 (1.00)	5986 (1.00)	5986 (1.00)	5986 (1.00)	5986 (1.00)	1.25	1.25	1.00	1.00	1.00	1.00

740 Figure legends

741
742 Fig. 1. Observed weather data for the 1999 and 2000 growing seasons. Solar radiation
743 ($\text{MJ m}^{-2} \text{d}^{-1}$) shown in the upper plot, precipitation (rain – mm) in the middle, and
744 maximum temperature ($^{\circ}\text{C}$) (solid line), minimum (dashed line) in the lower plot.

745
746 Fig. 2. Predicted (lines) versus observed (symbols) harvest biomass components (pod,
747 stem and seed) in 1999 (A) and 2000 (B). Error bars indicate the 95% confidence
748 intervals in the field experiment. Legend: ambient CO_2 (Amb), twice-ambient CO_2 (En.).

749
750 Fig. 3. Effects of solar radiation on seed yield at ambient and elevated CO_2
751 concentrations in irrigated and non-irrigated simulations for 1999 and 2000. Legend:
752 ambient CO_2 (Amb), twice-ambient CO_2 (En.), irrigated (irr.), non-irrigated (non-irr).

753
754 Fig. 4. Effects of precipitation on seed yield at ambient and elevated CO_2
755 concentrations in irrigated and non-irrigated simulations for 1999 and 2000. Legend:
756 ambient CO_2 (Amb), twice-ambient CO_2 (En.) .), irrigated (irr.), non-irrigated (non-irr).

757 .
758
759 Fig. 5. Effects of average seasonal temperature on seed yield at ambient and elevated
760 CO_2 concentrations in irrigated and non-irrigated simulations for 1999 and 2000.

761 Legend: ambient CO_2 (Amb), twice-ambient CO_2 (En.) ., irrigated (irr.), non-irrigated
762 (non-irr).

763

764 Fig 6. Relationship between seasonal average temperature and (a) anthesis and (b)
765 physiological maturity for 1999 and 2000 ambient CO₂ conditions. Legend: ambient
766 CO₂ (Amb), twice-ambient CO₂ (En.) ., irrigated (irr.), non-irrigated (non-irr).

767

768 Fig. 7. Factor separation plot for 1999 (a) and 2000 (b) soybean crop differential yield
769 (kg ha⁻¹). Legend: ambient CO₂ (Amb), twice-ambient CO₂ (En.) ., irrigated (irr.), non-
770 irrigated (non-irr).

771

772 Fig. 8. Simulated canopy and pod biomass for non-irrigated soybeans in ambient (a)
773 and enhanced (b) CO₂ in 2000 for the four components included in the calculation of the
774 radiation-temperature interaction factor (E_{RT}). Definitions for the components are

775 included in Table 2.

776

777

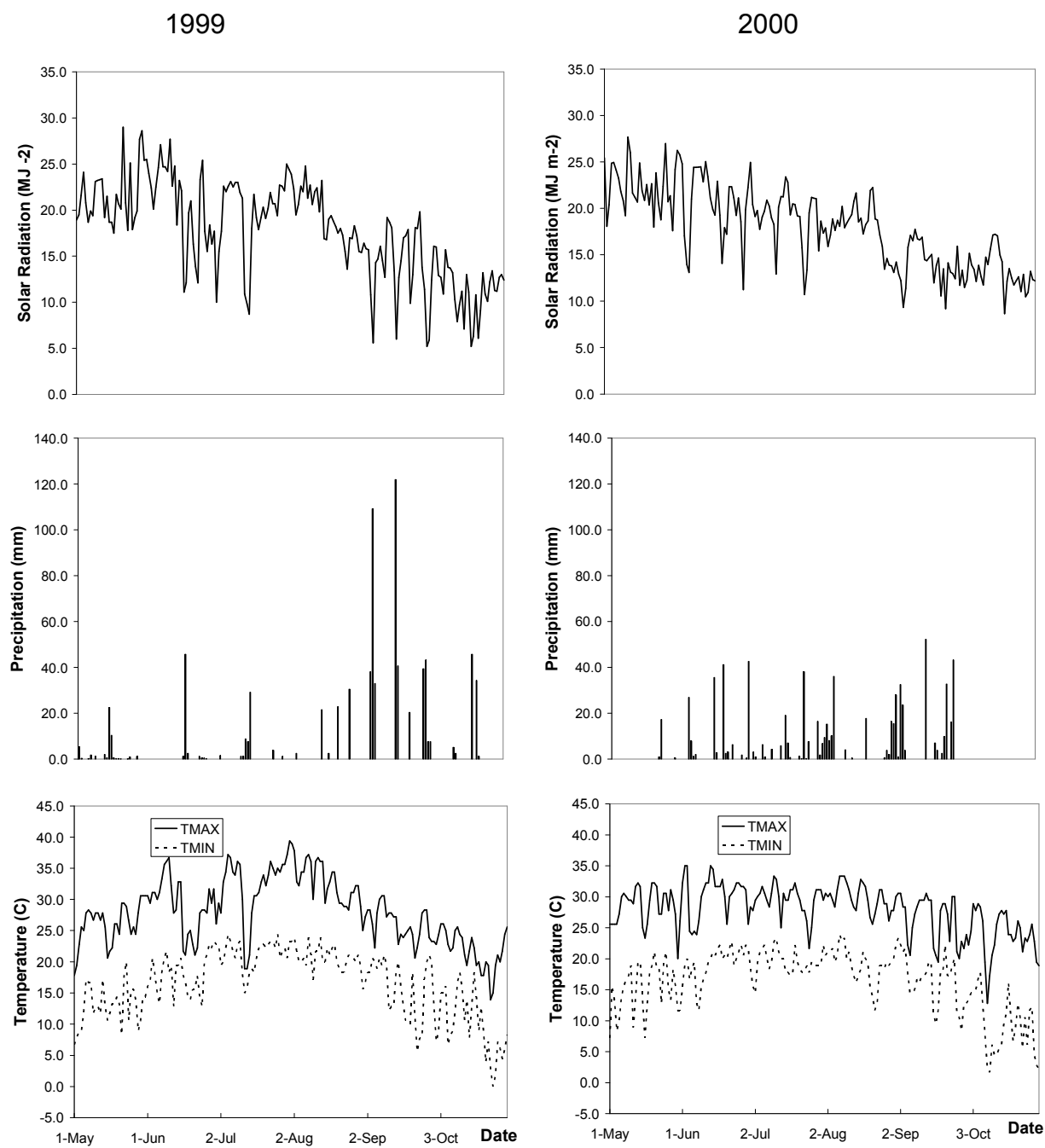
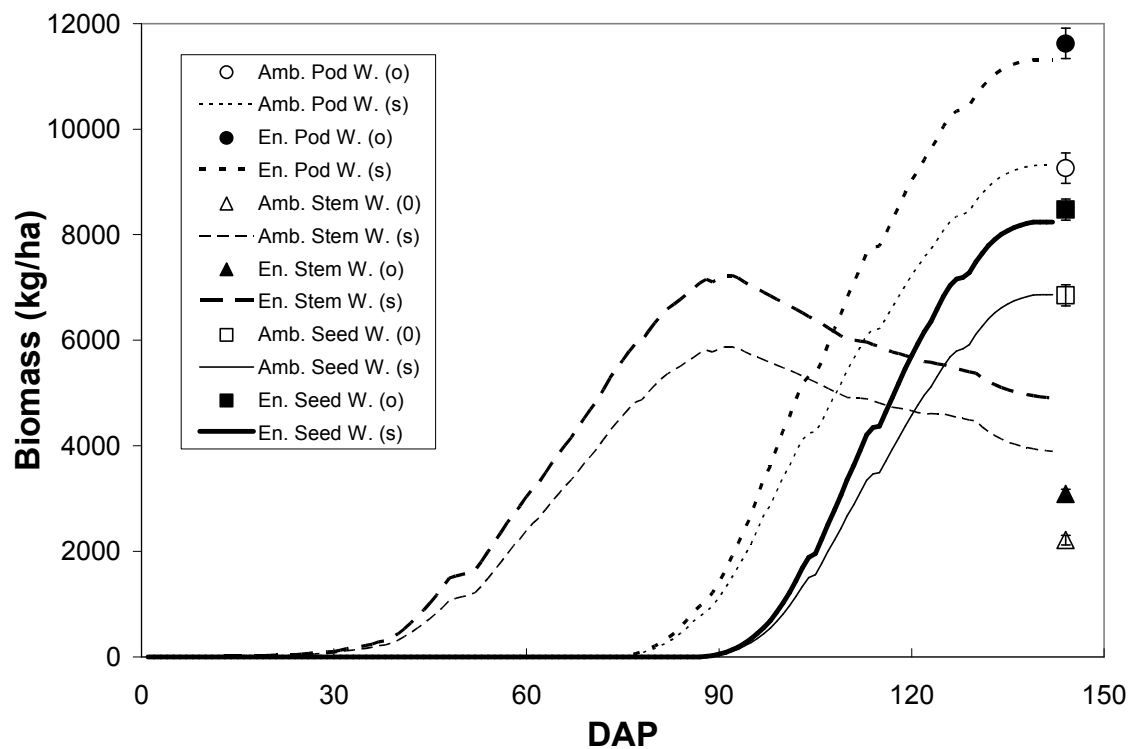
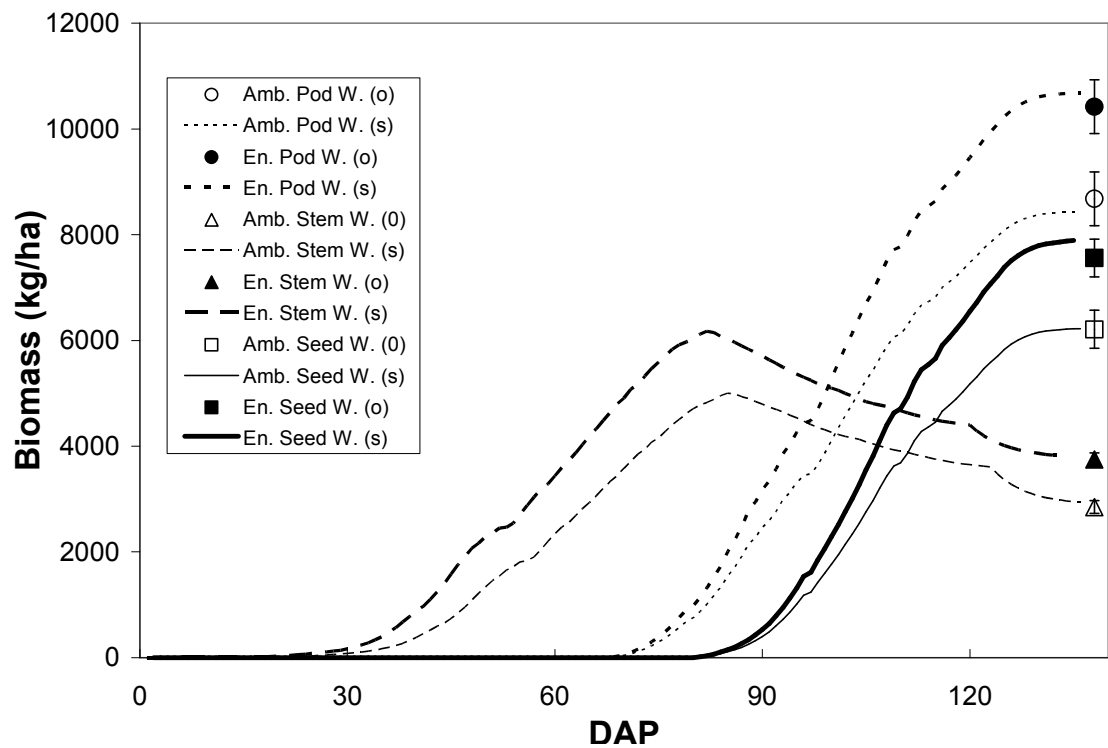


Fig. 1: Observed climate data for the 1999 season (left) and 2000 season (right). Solar radiation (MJ m⁻² day⁻¹) shown in the top plot, precipitation (rain – mm) in the middle, and Max. temp. (°C) (solid line), min. (dashed line).

778
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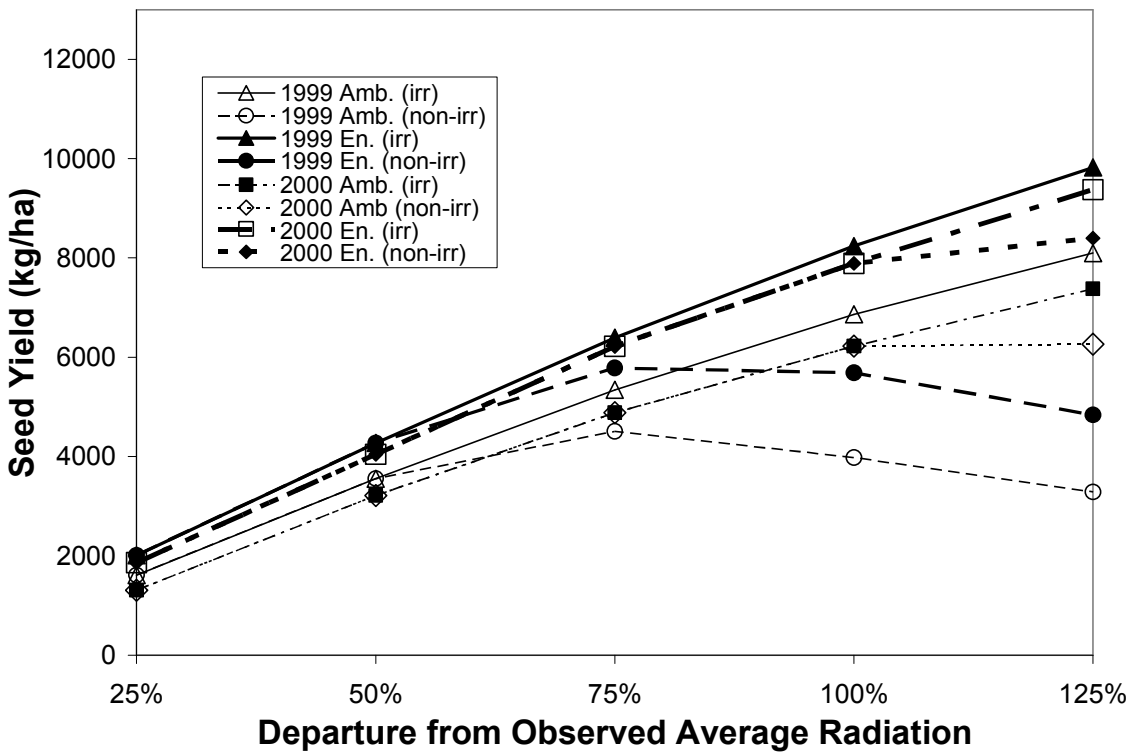


780



781

Fig. 2: Predicted (lines) versus observed (symbols) harvest biomass components (pod, stem and seed) in 1999 (top) and 2000 (bottom). Error bars indicate the confidence intervals in the field experiment.



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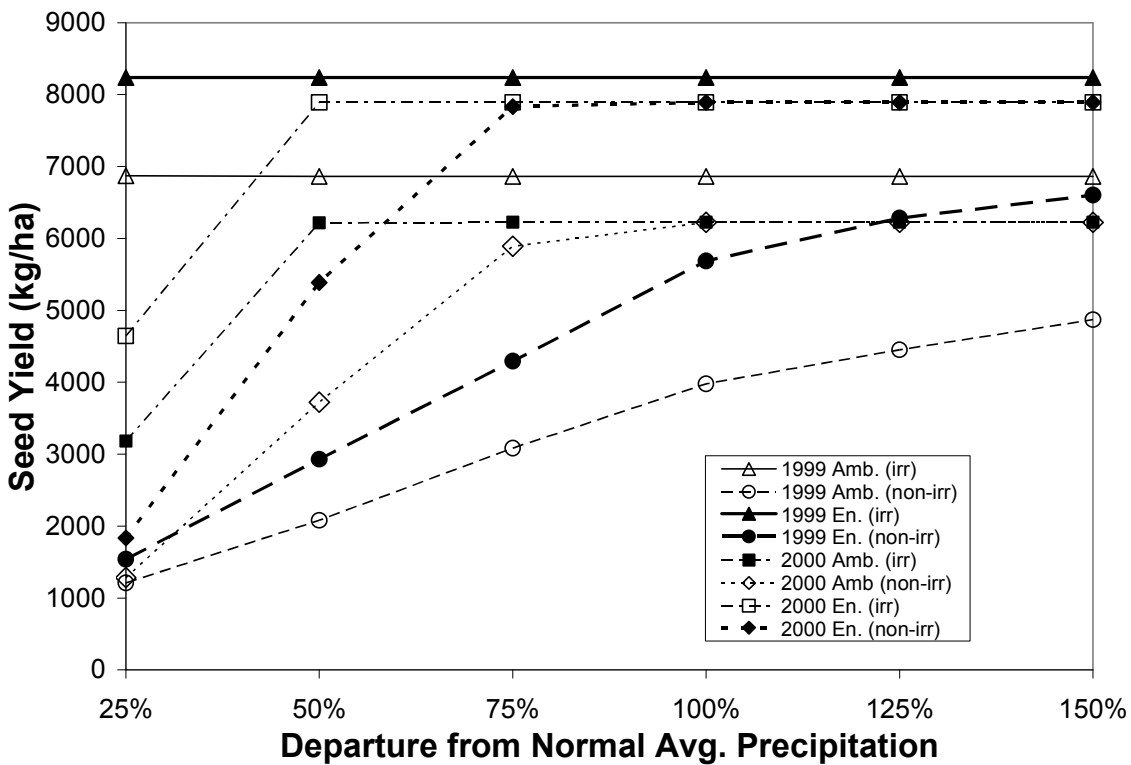
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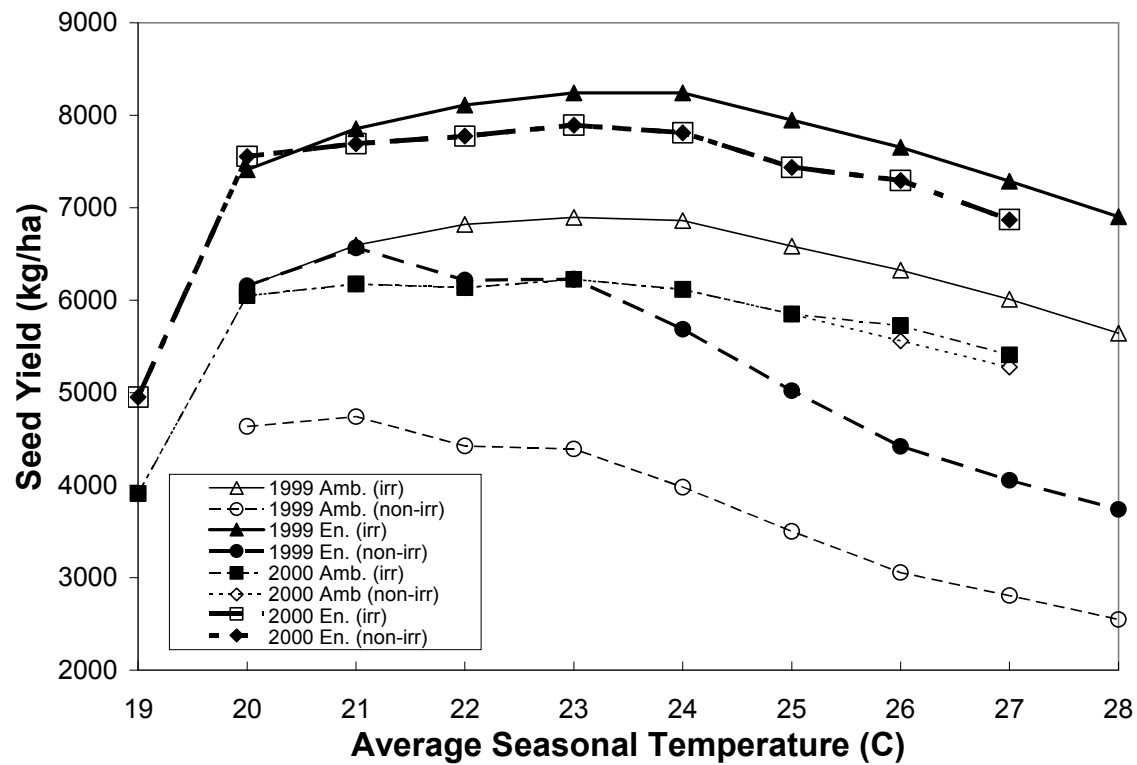
787

Fig. 3. Non-linear effects of ambient and enhanced CO₂ in irrigated and non-irrigated environments for 1999 and 2000. Irrigated treatments tend to have a steady increase while non-irrigated treatments peak in yield at 75% or 100% observed average radiation.



788

Fig. 4 Same as Fig. 3 but for precipitation changes. Irrigated treatments show very little to no change in seed yield for irrigated treatments, especially in 1999. Non-irrigated treatments see steady increases.



789

Fig 5. Same as Fig. 3 but for changes in temperature. Temperature range for 1999 is from 20°C to 28°C and 19°C to 27°C for 2000. Irrigated treatments as well as all 2000 treatments have their highest yields between 22°C and 23°C

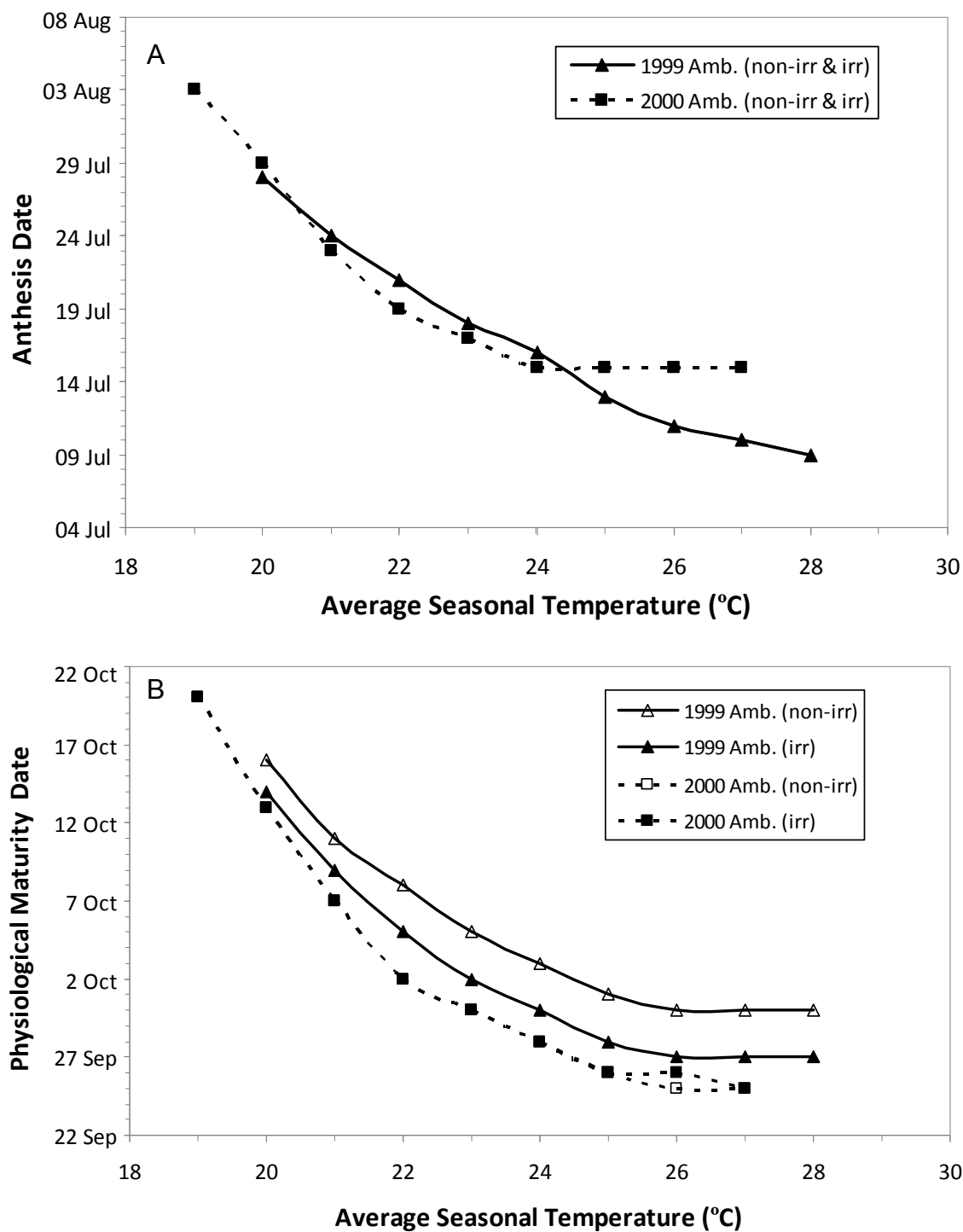
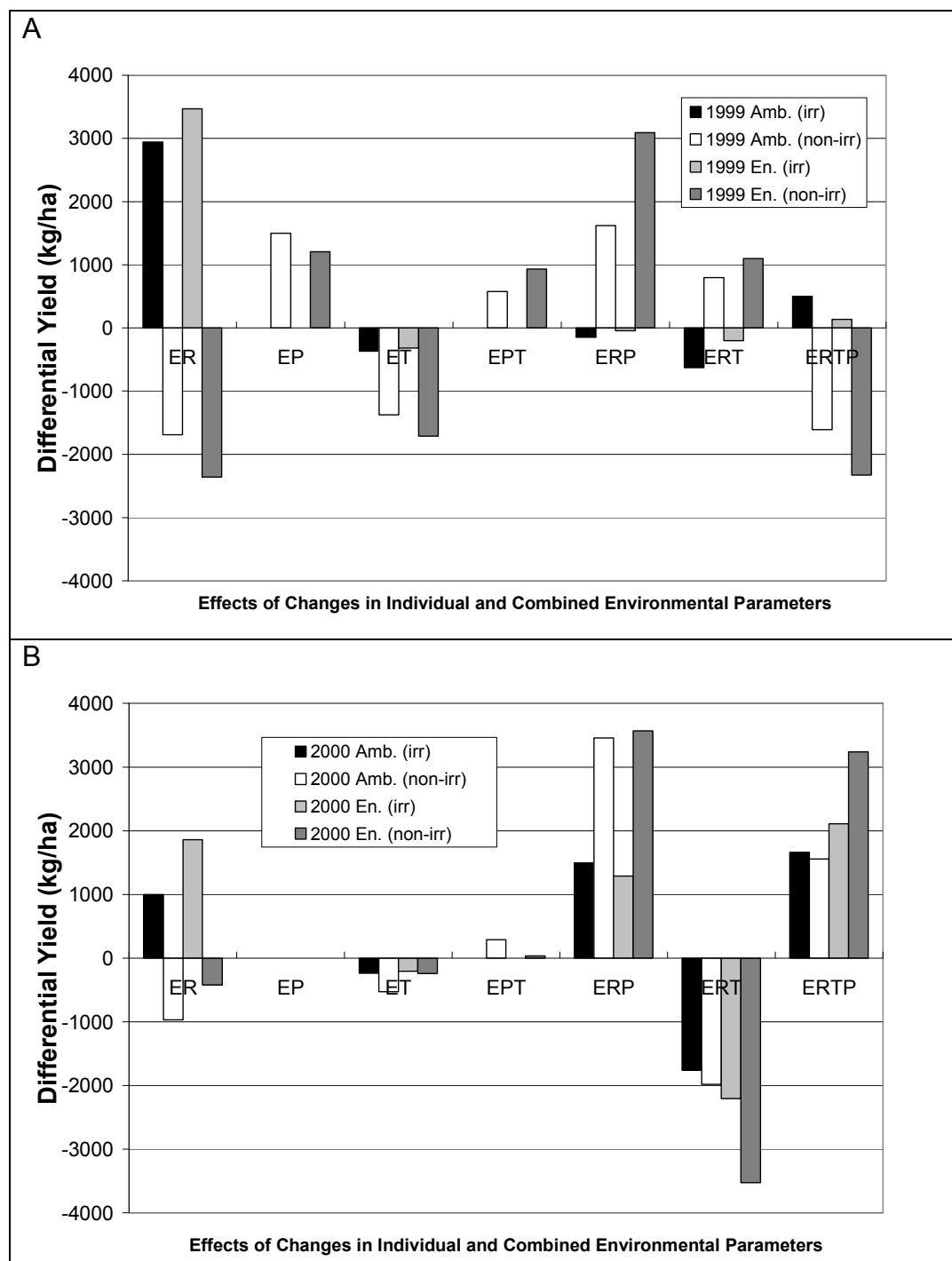


Fig 6. Relationship between seasonal average temperature and (a) anthesis and (b) physiological maturity for 1999 and 2000 ambient CO₂ conditions.

790



791

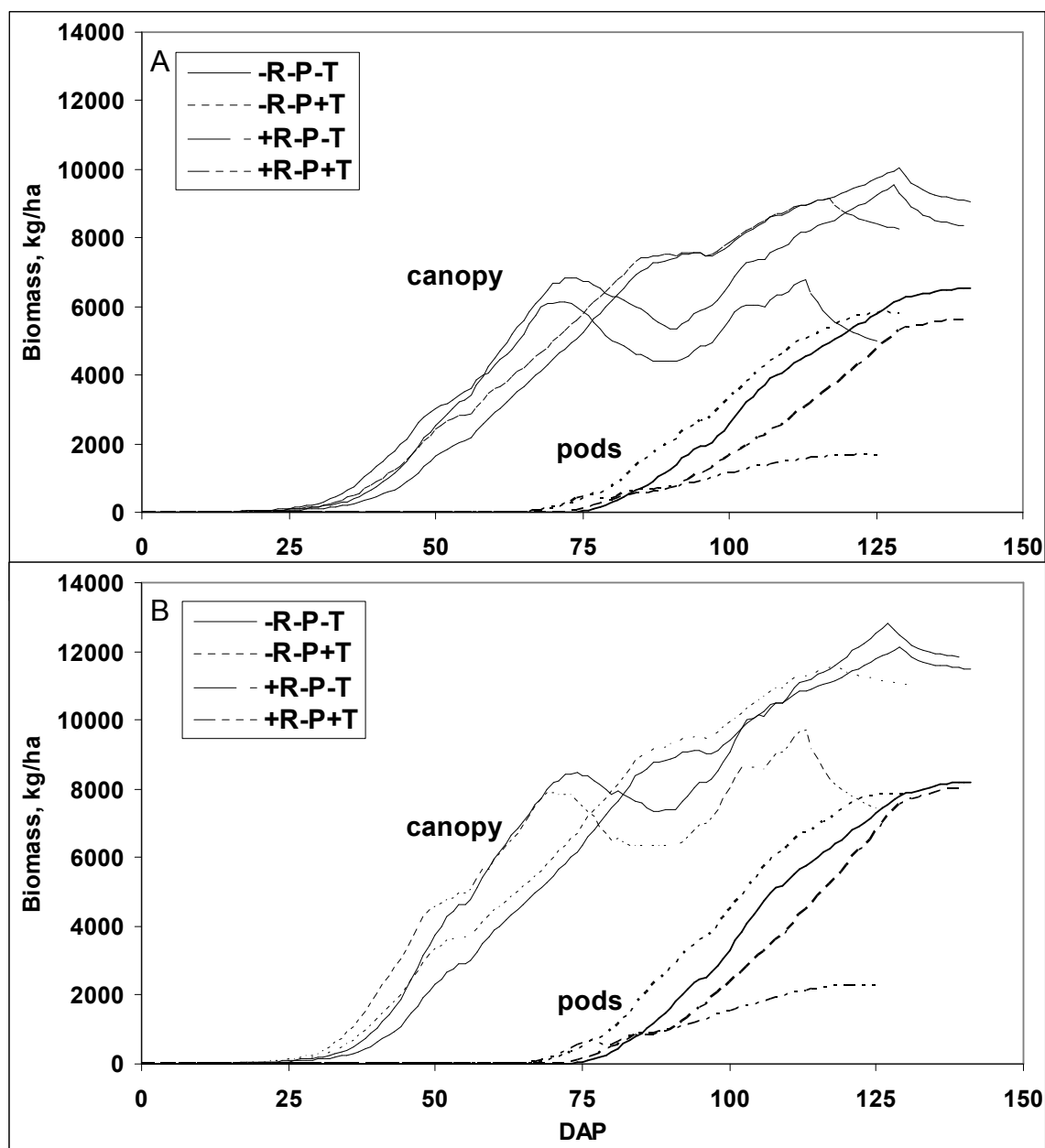
792 Fig. 7. Factor Separation Plot for 1999 (a) and 2000 (b) soybean crop differential yield (kg ha^{-1})

793 Some of the main differences between the two seasons include the contributions by radiation (ER)

794 that are positive for all treatments in 2000 but have negative values for non-irrigated in 1999.

Conversely, the radiation-temperature interaction contribution is all negative for 2000 but has positive numbers for irrigated treatments in 1999.

795



796

Fig. 8. Simulated canopy and pod biomass for non-irrigated soybeans in ambient (a) and enhanced (b) CO₂ in 2000 for the four components included in the calculation of the radiation-temperature interaction factor (E_{RT}). Definitions for the components are included in Table 2.