ABSTRACT

MERA, ROBERTO JAVIER. The Effect of Multiple Environmental Changes on Crop Model Response and Potential Improvements of Dynamical Land Surface Models. (Under the direction of Dev Niyogi and Fredrick Semazzi.)

Agriculture has become a dominant form of land cover through changes in land use, and is increasingly being considered an important part of land surface and general circulation models. The objective of this study is to analyze crop models' responses to multiple changes in environmental conditions and to provide sources for potential improvements of dynamical land surface models. We address these goals by evaluating a crop model's response to changes in observed climate and future projections from a regional climate model (RCM), and discerning the effect of multiple environmental changes on C_3 and C_4 plants.

After successful validation of the model CROPGRO (soybean), we modified prescribed variations in solar radiation (R), precipitation (P), temperature (T), in the observed climate for a field experiment's ambient and enhanced carbon dioxide (CO_2) treatments. We found that the impact of changes in radiation and precipitation is affected by water stress, while temperature effects differ greatly for varying water-stress conditions and CO_2 concentrations.

We then analyzed the model's responses to data from an RCM simulation for current and transient increase in atmospheric CO_2 levels. Using model data and calculated anomalies, we found that higher temperatures had a negative impact on crops. We found that higher CO_2 reduced the impact of water stress.

Finally, we investigated the effect of individual versus simultaneous changes in R, P, and T on plant response in a C_3 (soybean) and a C_4 (maize) plant. Using CROPGRO/SOYGRO and CERES-maize, we found that soybean and maize respond

differently for R, P, and T and maize is more sensitive. The results also show that simultaneous changes in variables do not necessarily agree with individual changes.

Our findings suggest that there is good potential for using the crop models within dynamical land surface modeling systems for current and doubled CO_2 scenarios. Further, our results indicate that additional considerations for ozone and process-level formulation that account for radiation changes should be added to the model.

THE EFFECT OF MULTIPLE ENVIRONMENTAL CHANGES ON CROP MODEL RESPONSE AND POTENTIAL IMPROVEMENTS OF DYNAMICAL LAND SURFACE MODELS

by

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DEDICATION

To my wife, my parents, and my brothers for their support, encouragement, patience, and faith in me throughout my studies. For my family and friends, past and present, for helping me become the person I am today. And to New Orleans, for everything, may it always be my home.

BIOGRAPHY

Roberto Javier Mera was born in the city of Guayaquil, Ecuador, in 1978. He moved to New Orleans, USA, in 1990 where he attended Benjamin Franklin High School and graduated with honors in 1997. Roberto decided to drastically change the scenery by becoming a student at the University of North Carolina at Asheville where he would fulfill his desire to become a meteorologist. After an unfortunate hiatus in 1998 and 1999, he returned to school in the 2000 fall semester where he continued with his studies in meteorology. He was in the Dean’s List on several semesters and became a member of the Sigma Delta Pi National Hispanic Honor Society. During the summer between his Junior and Senior years, he conducted undergraduate research in Ecuador on the relative economic effects of the 82-83 and 97-98 El Niño events in that country. He graduated in 2003 with a major in Meteorology and a minor in Spanish. He began his master’s studies in Atmospheric Science at North Carolina State University in the fall of 2003. Roberto has served as a research assistant at NC State and participated in research conducted at Purdue University and for USDA-ARS. He was accepted as a doctoral student in 2005. His interests include model skill and value measurements, regional climate modeling, climate-crop model coupling, and biosphere-atmosphere interactions.

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1. INTRODUCTION

1.1 Agriculture and Land Surface Models

The Earth's climate is changing due to both natural and anthropogenic forcings (IPCC 2001). Factors such as increasing greenhouse gases, aerosols, and land use changes contribute to changes in the climate. Droughts, floods, and weather extremes such as severe storms or prolonged periods of unseasonably cold or warm temperatures can have a significant effect on agriculture. Agriculture is one of the most climate-sensitive fields, but recently it has been found that its reciprocal effects on the environment could be a potential contributor to climate change (Rosenzweig and Parry, 1994; Foley et al., 2005). Possible changes in the climate due to land cover/land use change (LCLUC) and increases in carbon dioxide (CO_2) could provide increased complexity in patterns of regional productivity, and the changes that its feedbacks may incur in the atmosphere.

The potential benefits of analyzing a crop's response to changes in the climate could help diagnose how modifications in agricultural patterns may affect the atmosphere. Agriculture plays a major role in regional climate change through its influence on LCLUC. These changes, in turn, affect agricultural productivity through changes in the environment. Global climate model (GCM) results have been shown to have inadequate spatial scales to adequately address these potential changes because of their coarse resolution (Gates, 1985; Robinson and Finkelstein, 1989; Lamb, 1987; Smith and Tirpak, 1989; Cohen, 1990). There is a considerable mismatch of scales between coarse resolution GCMs (100s of km) and the scales of interest for regional impacts (at least an order magnitude finer scale) (IPCC, 1994; Hostetler, 1994). For instance, mechanistic models (e.g. CROPGRO, CERES-Maize) employed to simulate the ecological effects of climate change usually operate at spatial resolutions varying from single plants to a few hectares (Mearns et al., 2003). Results from these models may be highly susceptible to fine-scale climate variations that may be embedded in coarse-scale climate variations, especially in regions with complex topography, coastlines, and in those with highly heterogeneous land surface covers (Mearns et al., 2003).

The addition of agricultural effects on the environment has been explored to diagnose its impact on climate at the regional scale (Tsvetsinskaya et al., 2001; Feddema et al., 2005). Statistically significant changes (at the 0.05 level) in latent heat and sensible heat have been found in extremely dry conditions as a response to changes in leaf area index (LAI) values through the incorporation of crop model processes from CERES-maize (Tsvetsinskaya et al., 2001). Other important variables, such as evaporation and transpiration, were also found to be affected by changes in LAI. This effect followed a distinct diurnal pattern that was more pronounced in drier conditions.

The study by Feddema et al. (2005) shows that agricultural expansion under the International Panel on Climate Change (IPCC) Emissions Scenario *A2* scenario had significant effects in the mid-latitudes producing cooler temperatures with a smaller mean daily temperature range over many areas. It was also found that the *A2* scenario, with elevated values of CO_2, produced significant changes that were often opposite those in the *B1* (lower CO_2 levels) scenario.

Unlike previous research that compared past and present climates through the inclusion of potential and current vegetation, respectively, a recent study focused on the evolution of vegetation distribution in the United States for the past 300 years (Roy et al., 2003). The study utilized NASA's Ecosystem Demography (ED) computer model, which allows for the study of land use and climate change in a broad range of scales, and found that the expansion of agriculture since 1700 caused significant cooling (~0.5C) in parts of the Great Plains and Midwest. It is believed that temperature changes in the mid-latitudes has occurred due to increases in evapotranspiration from farmlands as well as increased surface albedo (Sellers et al., 1996; Betts, 1999; Bonan, 1999; Zhao et al., 2001; Roy et al., 2003; de Noblet-Ducoudré, 2005).

Past studies also show that a projected lengthening of the growing season in mid-latitudes (Myneni et al., 1997) could result in increases in biomass density, biogeochemical cycling rates, photosynthesis, respiration, and fire frequency, thus leading to considerable changes in albedo, evapotranspiration, hydrology and carbon balance (Bonan et al., 1992; Thomas and Rowntree, 1992; Harding and Pomeroy, 1996; Levis et al., 1999). A number of studies have also focused on interactions between climate and vegetation over the tropics, where conversion of forests to grasslands and croplands has been occurring for years (e.g., Nobre et al. 1991; Xue and Shukla 1993; Polcher et al. 1996).

The role of farmlands in the global scale has also not been considered in studies such as Dufresne et al. (2002), Friedlingstein et al. (2003), and Cox et al. (2000), where the interactions between land surfaces and increasing levels of CO_2 was explored. Global biosphere models summarize natural biogeochemical and biophysical processes to simulate important ecosystems processes (e.g., photosynthesis, respiration, etc.) at a large spatial scale, and are often designed to be coupled with atmospheric general circulation models (GCMs) (Gervois et al., 2004). These global models generally have few plant functional types, and they treat croplands in a simplistic manner.

Indeed, recent studies have suggested that croplands effects on the atmosphere may be playing a major role in severe weather patterns (Pielke et al., 1997), and the formation and intensity of tornadoes through high levels of transpiration (D. Niyogi, Personal Communication, 2006). As is the case with global models, the majority of research seeking to address the impact of land use on regional scales has treated croplands as “modified grasslands.” Crop models, which are able to represent agroecosystems realistically, have only been tailored for specific predictions and analyses at the site or field level, and their incorporation into global and regional models has seldom been considered (Gervois et al., 2004).

There is a need for closer coupling between models of climate, crops and hydrology, in order to get better representations of climate change. Recent research has aimed at acquiring crop-specific information for dynamical land surface models through the use of crop models (Gervois et al., 2004; Betts, 2005). There have been studies performed integrating crop models into land surface models for global scales (Gervois et al., 2004; Osborne, 2004), and regional scales (Pan et al., 2004a; Pan et al., 2004b). This type of research has shown promising results that suggest additional work is necessary for introducing crop models to land surface models in order to attain proper representation of cropland-climate interactions. Areas with heterogeneous landscapes are critical to reproducing important features of the climate, and applications within these regions require RCMs with the capability to discern fine-scale processes (Mearns et al., 2003). Regions with heterogeneous land surfaces include the southeastern US, the Sahael, and inland Australia, where high resolution modeling is highly recommended (given a particular context, resource, and study goal) (Mearns et al., 2003).

Our aim in this study is to analyze a crop model’s response to multiple changes in the environment (e.g. CO_2, radiation, precipitation, temperature) and management (irrigation), and thus acquire a representation of key aspects that should be taken into consideration for the integration of crop modeling systems within dynamical land surface modeling systems. We present this approach through the description of our study (section 1.2).

1.2 Description of Study

Greenhouse gases have increased exponentially since the industrial revolution (IPCC, 2001). Climate simulations using GCMs have consistently predicted large scale climatic responses due to increases in greenhouse gases like CO_2 from anthropogenic sources (IPCC, 2001; Meehl et al., 2005). The impact of increasing CO_2 on agriculture has been major focus of climate change studies. A wide variety of field experiments have shown that increased CO_2 tends to stimulate plant growth (Cure and Acock, 1986; Bazzaz, 1990; Rogers and Dahlman, 1993; Rogers et al., 1994; Drake et al., 1997; Curtis and Wang, 1998; Ainsworth et al., 2002; Jablonski et al., 2002; Booker et al., 2005). Another group of studies has shown that plant responses may vary by considerable amounts, due mainly to differences in experimental protocols and genotypes, and plant growth environment (Ainsworth et al., 2002; Fiscus et al., 2001; Kimball, 1983; Eastman et al., 2001; Niyogi and Xue, 2005).

Crop models provide a method to test multiple changes in environmental conditions to construct future projections of agricultural productivity. For instance, the model CROPGRO (soybean), has been used to discern the effect of elevated levels of CO2 has on soybean crops (Cavazzoni et al., 1997; Boote et al., 2002a; Wolf, 2002a; Alagarswamy et al., 2006). These studies, however, have not addressed how simultaneous changes in weather variables such as precipitation (P), solar radiation (R), and temperature (T) may interact with varying levels of CO_2 and irrigation practices. Thus, the objective of our first study is to compare the crop model's response to individual and simultaneous changes in climate parameters in enhanced and ambient CO_2 conditions, irrigated and non-irrigated treatments, and mixtures of the two. For this, we use observed weather data from a field experiment after successful model validation.

Regional climate models (RCMs) present an alternate way to test CROPGRO's response to environmental changes. They have been shown to be superior to GCMs through their ability to enhance spatial and temporal differences in crop performance trough higher resolution (Semenov and Jamieson, 2000; Cocke and LaRow, 2000; Guerreña et al., 2001). Recent studies suggest that RCMs have the ability to approximate regional and local climate change scenarios that would enable application for predicting impacts on agriculture (Giorgi et al., 2001; Hanley et al., 2002). RCMs have previously been used to drive crop models for climate change sensitivities and elevated CO_2 effects (Guerreña et al., 2001; Hanley et al., 2002; Adams et al., 2003; Carbone et al., 2003; Tsvetsinskaya et al., 2003).

Recent advances in regional climate modeling have allowed for higher resolution scales that can capture fine scale processes that may influence regional and local responses to changes in large scale patterns due to anthropogenic and non-anthropogenic causes (Diffenbaugh et al., 2005). Such fine scales could prove beneficial for coupling the RCM with a crop model by creating more representative local conditions, and reproducing climate extremes that may be useful in analyzing a crop's response. In our second study, we will use RCM data to drive CROPGRO at a variety of CO_2 concentrations to discern the impact of climate change on the relationship between crop yields and environmental variables like soil moisture, precipitation, effective precipitation, and temperature. We develop model anomalies to lessen the effects of model biases and noise at the agricultural scale, and compare them against model runs using observed weather data and original RCM projections.

Recent studies suggest that different aspects of climate change (e.g. solar radiation, precipitation, and temperature) should be addressed beyond increasing amounts of CO_2 on regional productivity (Hansen et al., 2002; Pielke et al., 2001). Variations in atmospheric radiation can alter hydrological cycles (Ramanathan et al. 2001), the carbon cycle (Niyogi et al. 2004), and evapotranspiration (Pielke et al. 2001). Earlier studies suggest that precipitation is the leading climatic factor affecting crops (Rosenzweig and Tubiello, 1997; Iglesias et al., 1996). It's been shown that water deficit can reduce the overall biomass of soybean, regardless of CO_2 enrichment (Ferris et al., 1999). Studies of crop's responses to climatic factors have made it evident that complex interactions due to precipitation patterns greatly impact regional productivity.

In addition to the study of precipitation changes, a number of studies have also focused on the influence that radiative changes may have on crops. Such work has focused on crop sensitivity to ultraviolet radiation (Booker et al., 1992; Fiscus et al., 1994; Miller et al. 1994; Mark and Tevini, 1997), and radiative properties like diffuse radiation (Chamedies et al. 1999; Niyogi et al. 2004). Biospheric productivity and structure could be impacted by increasing aerosols and clouds due to biomass burning or volcanic eruptions (Hansen et al. 1999; Gu et al. 2003). The natural and anthropogenic aerosols could contribute to reduction in the solar radiation absorbed by the Earth's surface by absorbing solar radiation, and reflecting it into space. A study by Pielke et al. (2005) suggests that this could produce a redistribution effect on surface heating and could change agricultural productivity in certain areas.

Temperature is another factor that can affect agricultural productivity (Fiscus et al., 1997). Changes in temperatures influences photosynthesis, respiration, transpiration rates, plant development, and sugar storage. Complex interactions between changes in radiation and temperatures can incur a variety of effects. Increasing aerosols can typically reduce surface temperatures by lowering surface radiation levels. The composition of the aerosols adds to the complexity of this interaction, since carbon dominated aerosols may cause warming while sulfate aerosols may induce further cooling (Pielke et al., 2005).

Water vapor pressure deficits in the air can be affected by changes in temperature, thus impacting the water use from agricultural landscapes (Kirschbaum, 2004). This feedback can cause considerable modifications in temperature and evaporation/transpiration through changes in transpiration and contribute to regional changes in precipitation and cloudiness, leading to changes in radiation (Pielke et al., 2001). Thus, it is important to recognize that environmental changes other than increasing CO_2 levels (e.g. radiation, precipitation, temperature) should be considered for their effect on regional productivity.

Past studies have shown the potential for interactive effects of multiple environmental factors on the plants' response by assessing the role of multiple effects and isolating individual impacts of climate change (Kirschbaum, 1994; Idso & Idso, 1994; Ham et al., 1995; Drake et al., 1997; Eastman et al., 2001). Thus, in the third part of the study, we seek to develop an analysis to evaluate the individual and multiple interactions of radiation, temperature, and precipitation changes on regional productivity of C_3 (soybean) and C_4 (maize) crops.

We present our study as follows. Section 2 discusses crop model sensitivity to multiple environmental changes simulated over a field experiment. In section 3 we explore the effect of environmental forcing on improving dynamical land surface models by testing a crop model with data from an RCM. In section 4 we explore potential individual versus simultaneous climate change effects on soybean (C_3) and maize (C_4) crops through the use of an agrotechnology Model. Conclusions are presented in section 5, and an appendices are included in section 6.

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2. Soybean Crop Sensitivity to Climate Change at Ambient and Enhanced Carbon Dioxide Levels

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Abstract

Changes in regional weather and climate patterns have the potential to affect agricultural productivity. These effects may be enhanced or dampened by increasing levels of carbon dioxide in the atmosphere. The more basic responses of climate change can be detected in radiation (R), precipitation (P), and temperature (T). Past studies suggest that changes in these variables can have strong influences on crops. In this study, we address the effect of changes in R, P, and T, individually and in concert, at ambient and enhanced levels of carbon dioxide. We use model simulations of field experiments for soybean crops using the DSSAT: Decision Support System for Agrotechnology Transfer CROPGRO model. The model was configured over a field experiment station south of Raleigh, NC [35.8N, 78.6W]. Recorded weather and field conditions during that experiment in the 1999 and 2000 seasons were used in the model. The model had fairly accurate predictions for simulated yield and partitioning response to ambient conditions in 1999 and 2000, as well as enhanced conditions in 2000. Values for the 1999 season were significantly underestimated. Once the model had been configured, we studied responses to individual changes in R and P (25%, 50%, 75%, 125%, 150%, 175%, 200%) and T (±1°C, ±2°C, ±3°C, ±4°C) with respect to observed conditions during those seasons at ambient and enhanced CO_2 concentrations, and in

irrigated and non-irrigated conditions. Subsequently, simultaneous changes were performed as follows: ±50% of observed precipitation, ±25% of observed solar radiation, and ±2°C of the observed temperature. Interactions and direct effects of individual versus simultaneous variable changes were analyzed. Results from the individual changes indicate: (i) precipitation changes are most sensitive for water stressed plants; (ii) Radiation impact is non-linear but is affected by irrigation; (iii) Temperature effects are non-linear and differ greatly for water-stress conditions and CO_2 concentrations. Results for simultaneous change analysis indicate that water stress has a prominent role in how these variables interact with each other and with increases in CO_2. Study results indicate a need for performing simultaneous parameter changes that include irrigation procedures and varying levels of CO_2 in order to assess the response of crop yield from projected climate change. Future climate change impact studies for CO_2 scenarios should consider multivariable, ensemble approaches to get a better representation of the potential outcomes.

2.1 Introduction

In recent years, a variety of field experiments have been conducted to analyze the effects of climate change on agricultural systems (Allen et al., 1987; Booker et al., 1992, 1997, 2005; Ferris et al., 1999; Fiscus et al., 1994; Sims et al., 1998). Models such as SOYGRO/CROPGRO (Jones et al., 1989; Jones et al., 2003) have been used extensively in recent years to provide future projections (Wolfe and Erickson, 1993; Mearns et al., 1992, 1997; Easterling et al., 1993). Analyses to assess the impact of climate change on agricultural production and agrotechnological adaptation are some of the ways in which CROPGRO and other Decision Support System for Agrotechnology Transfer (DSSAT) models (Hoogenboom et al., 2003) can be used effectively (Hoogenboom 2000).

Climate change studies benefit from the ongoing testing of the crop models through validation experiments using field data (Boote et al., 2002a, 2003). In one experiment, the modeled plant's reaction to temperature changes was tested against chamber-grown data and found to be fairly well correlated (Pan, 1996; Boote et al., 2002b). A detailed study by Boote et al. (2002a) comparing CROPGRO simulated leaf photosynthesis to published data from Sims et al. (1998), Griffin and Luo (1999), and Harley et al. (1985), also found good agreement. CROPGRO and other models have been used to study the impacts of precipitation , temperature, and solar radiation changes (Hansen et al., 1996; Wang et al., 2001; Magrín et al., 2002; Wolf and van Diepen, 1995; Brown and Rosenberg, 1997; Southworth et al., 2000; Wolf, 2002b). Generally, alterations in the precipitation factor translated into significant changes in yield.

Site specific evaluations of the CROPGRO-Soybean model have occurred in several locations, such as Missouri (Wang et al., 2001), Hawaii (Ogoshi et al., 1998), and various other sites within the US including North Carolina (Boote et al., 1997). A multi-year, multi-state compilation of studies by Jones et al. (2004), concluded that CROPGRO-Soybean could be used to simulate a variety of environmental conditions including the drought response of soybean cultivars.

A study by Boote et al. (2001) utilized a variety of growth analysis datasets to investigate the effects of temperature and water deficit on C balance and N balance processes of the CROPGRO-Soybean model. The study also reviewed existing literature to identify data from controlled-environment studies for testing soybean response to temperature and CO_2, and identified data to test the accurate simulation of the final yield given by the model.

A number of climate-change studies with CROPGRO have probed the effects of enhanced amounts of CO_2 in the atmosphere. However, there are relatively few evaluations of the CROPGRO model under enhanced CO2 conditions. For example, Wolf (2002a) and Alexandrov et al. (2002) considered a scenario that included CO_2 enrichment in addition to other variable changes such as solar radiation and temperature. Unsworth and Hogsett (1996) found that elevated CO_2 increased the rate of net photosynthesis and decreased stomatal conductance, which in turn significantly enhanced dry matter production and yield (. Boote et al.'s (2002a) validation experiment also evaluated the effects due to changes in CO_2. In their study, the modeled effects of CO_2 were scaled down to specific leaf area (SLA) and nitrogen (N) concentration, intercellular CO_2 assimilation, and canopy photosynthesis using field data from Sims et al., (1998) Griffin and Luo (1999), Harley et al. (1985), Griffin et al. (1999), Valle et al. (1985). The model was found to be in good agreement with their data.

One of the reasons for the limited model evaluations under enhanced CO_2 conditions is the need for accurate field data. The majority of field studies have shown that increased CO_2 tends to stimulate plant growth (Cure and Acock, 1986; Bazzaz, 1990; Rogers and Dahlman, 1993; Rogers et al., 1994; Drake et al., 1997; Curtis and Wang, 1998; Ainsworth et al., 2002; Jablonski et al., 2002; Booker et al., 2005). Previous studies have also shown that the outcomes of these experiments can often vary by substantial amounts, due mainly to differences in genotypes, differences in experimental protocols, and plant growth environment (Ainsworth et al., 2002; Fiscus et al., 2001; Kimball, 1983; Eastman et al., 2001; Niyogi and Xue, 2005).

To provide better control of environmental conditions, a range of field experiments have successfully utilized container-grown environments. Initially, there was skepticism as to whether the container-grown plants could appropriately represent real-world conditions (Ainsworth et al., 2002; Idso and Idso, 1994; Jarvis, 1989; Lawlor and Mitchell, 1991). One of the concerns was the possible root volume reduction due to small pots, which in turn could reduce photosynthetic capacity through carbohydrate source-sink imbalance (Arp, 1991; Thomas and Strain, 1991; Idso, 1994). However, studies such as McConnaughay et al. (1993) and Reekie and Bazzaz (1991) showed that response to CO_2 was not always decreased by the use of small pots. Only a couple of experiments have actually focused on comparing pot-grown and ground-based plants (Heagle et al., 1999; Booker et al., 2005). In Heagle et al (1999) it was found that even though the growth and plant biomass in the two rooting environments was different, relative growth and yield responses to elevated CO_2 were similar. These findings have been subsequently verified by Booker et al. (2005), where the CO_2 enrichment increased above ground biomass and total seed yield.

These recent experiments provide an opportunity for further CROPGRO model evaluations. For instance, the data from Booker et al. (2005) includes plants that are grown in the ground and exposed to both ambient and doubled concentrations of $CO_{2.}$

We had three objectives in this study. The first was to model the ground-grown soybean data from Booker et al. (2005) at normal and elevated atmospheric CO_2 levels. The second objective was to evaluate the CROPGRO-Soybean model for sensitivity to one-at-a-time and simultaneous changes in climate variables (rainfall, solar radiation, and temperature) under both ambient and elevated $CO_{2.}$ Our final objective was to assess simulated plant response to changes in irrigation strategy under ambient and enhanced CO_2 conditions.

2.2 Methodology

In order to configure CROPGRO-Soybean we have used data and analysis from Booker et al. (2005) in Raleigh, North Carolina. The model was tested to see how the results compared to the observations in terms of yield, anthesis date, physiological maturity date, harvest date, as well as pod, stem and seed weights (yield). Following the validation we modified the weather input data to study sensitivity to changes in individual climate variables (radiation, temperature, and precipitation (soil moisture)) as well as their interactions. Finally, we studied the relative effects and impacts of irrigation (soil moisture) and CO_2 changes on the crop. In this section we provide a summary of the field experiment, provide a description of the model, and the analysis approach (including a statistical factor separation / ANOVA-like technique) for extracting the interactions.

2.2.1 Model Calibration

Booker et al. (2005) compared growth and yield of container- and ground-grown plants under ambient and elevated levels of CO_2 and ozone (O_3). CROPGRO does not include O_3 interactions, nor was it designed for simulating container-grown plants. Hence we focused on simulating ground-grown plants under both ambient and elevated levels of CO_2 and ambient levels of O_3. This study utilized Essex soybean sown on 24 May 1999 and 31 May 2000 at a site 5 km south of Raleigh, NC. The soil was used was Appling sandy loam. Soybean was planted in rows with 1-m spacing and plant spacing of 5.5 cm (18 plants m^{-2}) and 7.7 cm (13 plants m^{-2}) in 1999 and 2000, respectively.

The ground plots in the field tests were fertilized according to soil test recommendations with 132.4 kg K ha^{-1} on 18 May 1999 and on 17 May 2000. The plants were irrigated as required to prevent visible signs of water stress. Total irrigation throughout the 1999 experiment was 33 cm; irrigation for the 2000 phase of the study was 5.3 cm. Plots were also sprayed to control spider mites and insects on 2 Aug. 1999 and 20 June, 28 June, 21 July and 1 Sept. 2000.

The Booker et al. experimental setup had controls for both CO_2 and ozone (O_3). Ozone was included in their analysis due to its toxicity to plants (Heagle, 1989; Heck et al., 1983; Morgan et al., 2003). The current version of CROPGRO, however, does not include O_3 interactions and hence we will only focus on the charcoal filtered (CF) data (i.e. without O_3). In order to see if CROPGRO could discern a difference in yields due to the presence of O_3, we compared data from Booker et al. (2005) against non-CF experiment (1995 exp). The modeled output did not show a significant distinction between the two, and has prompted us to suggest that an O_3 module should be added to DSSAT in order to facilitate the modeling of air quality effects on crops.

The experimental design in Booker et al. (2005) consisted of all combinations of two CO_2 treatments-and two O_3 treatments. There were three replicate chambers for each treatment. The CO_2 treatments were ambient (no CO_2 addition) and CO_2 enrichment of approximately 337 μmol mol^{-1} 24 h d^{-1} The plants were exposed to different levels of CO_2 in cylindrical open-top chambers, 3 m diameter × 2.4 m tall, and on a daily basis. The treatments began in mid-June and continued until mid-October, when plants in all treatments were at physiological maturity.

For the 1999 section of the experiment, the ground-grown plants were sampled for aboveground midseason biomass at 98 to 102 d after planting (DAP). At 162 to 164 DAP in the 1999 experiment, two 80-cm row sections in each of two rows were harvested for yield measurements. In the 2000 experiment, two 100-cm row sections in each of two rows were harvested for yield at 146 to 149 DAP. As with 1999, the dry mass of leaves, stems, branches, and pods was measured. (See appendix for simulation details).

2.2.2 Crop Model

We utilize the CROPGRO-Soybean model (Jones et al., 2003) as part of DSSAT (Hoogenboom et al., 2004) in this study. CROPGRO is a predictive, deterministic model which simulates physical, chemical, and biological processes in the plant and the surrounding environment. The model simulates crop yields and related agronomic parameters, and is set up to calculate primary plant processes as a function of weather, soil, and crop management.

CROPGRO is process-oriented and considers crop development, crop carbon balance, crop and soil N balances, and soil water balance (Boote et al., 1998). Crop development in the model is differentially sensitive to temperature, photoperiod, water deficit, and N stresses during various growth phases, and is expressed as the physiological days per calendar day (PD/day).

The model simulates changes in photosynthesis and evapotranspiration caused by elevated CO_2 (Tsuji et al., 1998). The evapotranspiration (ET) module of CROPGRO includes the ratio of transpiration in a CO_2 enriched atmosphere to that in ambient conditions in order to account for the effect of elevated CO_2 on stomatal closure, increased leaf area index, and the resulting potential transpiration. Leaf resistance is calculated as a function of prescribed CO_2 levels. The result of the ratio procedure is a lower transpiration rate per unit leaf area for increased CO_2 concentrations on a daily basis. In contrast, seasonal evapotranspiration may not change proportionally, and may actually be augmented due to higher biomass and the greater leaf area produced in an elevated CO_2 environment (Tsuji et al., 1998). In the model, ET is estimated following Priestley-Taylor method (Priestley and Taylor, 1972).

2.2.3 Analysis

For our comparisons between the modeled and observed we have selected specific items: anthesis and physiological maturity dates, pod and stem weights, and yield at harvest (seed weight). We calibrated the model using the observed data on soil type and crop management (see section 1.2.1). The model parameters and coefficients were adjusted for the ambient 1999 conditions. Only the planting dates and CO_2 concentrations were changes for the 2000 season. The irrigation schedule and amounts from the field experiment were also used for the 1999 season (no irrigation data was available for 2000).

Once the model had been calibrated and tested against the observations, we proceeded to analyze the different ways in which individual changes in weather variables (precipitation, temperature, solar radiation) could affect crop yield. Figures 1 and 2 show the variation in individual variables throughout the growing season for 1999 and 2000 respectively. We decided to alter the observed weather in both years by changing the daily precipitation (P) and solar radiation (R) values to be 25%, 50%, 75%, 125% and 150% of the observed values in the field experiment. For temperature (T), we changed the observations by ±1°C, ±2°C, ±3°C, and ±4°C for the daily values. These changes were then applied to all CO_2 and irrigation treatments.

The 1999 weather year file was also subjected to simultaneous changes in the variables to distinguish their interactions under irrigated and non-irrigated conditions for both of the CO_2 treatments. The same was done for the year 2000 except without irrigation changes. The variable modifications were performed as follows: ±50% of observed precipitation, ±25% of observed solar radiation, and ±2°C of the observed temperature. These ranges in the climate variables were based on the summary projections from climate model results and the analysis of past regional climate data for seasonal variations.

The only model output considered for the above analysis was the final yield at harvest (kg/ha). Crop management, soil type, and other specifications from the field experiment as given in section 2.2 were assumed in all simulations.

In order to examine the different contributions given by individual variable changes and their specific interactions we employed a statistical/factorial design called factor separation (Stein and Alpert, 1993). The direct effects of variables and interactions were calculated as follows:

$$E_0 = mRmPmT \quad (1a)$$

$$E_R = pRmPmT - mRmPmT \quad (1b)$$

$$E_P = mRpPmT - mRmPmT \quad (1c)$$

$$E_T = mRmPpT - mRmPmT \quad (1d)$$

$$E_{RP} = pRpPmT - (pRmPmT + mRpPmT) + mRmPmT \quad (1e)$$

$$E_{RT} = pRmPpT - (pRmPmT + mRmPpT) + mRmPmT \quad (1f)$$

$$E_{PT} = mRpPpT - (mRpPmT + mRmPpT) + mRmPmT \quad (1g)$$

$$E_{RPT} = pRpPpT - (pRpPmT + pRmPpT + mRpPpT) + (pRmPmT + mRpPmT + mRmPpT) - mRmPmT) \quad (1h)$$

The terms on the right hand side of the equation are the same as provided in Table 1. Terms on the left hand side of the equation are defined as follows: E_0 = background effect without R, P, T interactions; E_R, E_P and E_T = individual contributions by the variable; E_{RP}, E_{RT}, and E_{PT} = double interactions; E_{RPT} = triple interactions between R, P, and T. The E's in the equations represent the variable interactions. The E0 term is a negative interactions (-R-P-T) run, where the effects of the interaction were less than in the observed. This reduces background noise and facilitates the extraction of contributions from specific variables and interactions.

2.3 Results and Discussion

2.3.1 Environmental Conditions

The observed climate during the two seasons (Table 3) included a generally hot and dry summer for 1999 and a hot but wet summer for 2000, except for September, which was cooler and wetter in 1999 than in 2000. The observed mean CO_2 concentrations were 373 μmol mol^{-1} for ambient and 699 μmol mol^{-1} for the enhanced in 1999, and 369 μmol mol^{-1} ambient and 717 μmol mol^{-1} enhanced for 2000.

2.3.2 Model Validation

We were able to calibrate* CROPGRO-Soybean to simulate yield fairly accurately for ambient CO_2 conditions as shown in figures 3 and 4, with differences ranging from less than 1% of the measured yield in 1999 to 5% in 2000. Simulations for ambient in 1999 (373 μmol mol^{-1} 24 h d^{-1}) and 2000 (369 μmol mol^{-1} 24 h d^{-1}) were significantly close (correlation coefficient = 0.99) to the experimental data in terms of aboveground mass partitioning (stem, seed, and pod weights). Differences in pod weight were close to 600 kg/ha in 1999 and 400 kg/ha in 2000. The stem weight was overestimated by over 1000 kg/ha in 1999 while the 2000 season experienced minute differences below 100 kg/ha between observed and simulated. The anthesis and harvest dates were also simulated correctly at July 17th and October 10th respectively for 1999.

The 1999 enhanced (699 μmol mol^{-1} 24 h d^{-1}) simulation (figure 3) gave seed and pod weights at less than 1000 kg/ha and 400 kg/ha respectively over the observed, while strongly underestimating stem weight by close to 1500 kg/ha. The enhanced (717 μmol mol^{-1} 24 h d^{-1})

*See appendix section 6.5 for further information on calibration

2000 data was much closer to the observations than the previous year with seed and pod weights about 400 kg/ha below the observed. The stem weight had very little difference between observed and simulated. As can be observed, predictions by CROPGRO for the 2000 season are different from 1999: where seed and pods are underestimated and stem overestimated in 1999, 2000 shows more accurate predictions.

2.3.3 Individual Climate Variable Changes

In this section we discuss the response of the modeled soybean crop when individual changes in climate variables (solar radiation, precipitation, temperature) are made. Solar radiation is important for plants because of its direct contribution to photosynthesis and indirect effect on water use efficiency and the modification of surface energy. Figure 5 shows the non-linear effect of radiative fluxes on soybean crops as modeled by CROPGRO. The changes in yield vary accordingly to the season (1999, 2000), ambient and enhanced treatments, as well as irrigated and non-irrigated treatments.

Irrigated conditions for 1999 have their highest value (~9000 kg/ha for enhanced and ~7000 kg/ha for ambient) at 125% of the observed level with significant differences (~2000 kg/ha) among them starting at 100%. The final yields are generally closer (~400 kg/ha) below this level. The non-irrigated versions of the two CO2 treatments in 1999 have their largest yield values (5000 kg/ha enhanced, ~4000 kg/ha ambient) between 75% and 100% of the observed. There is a significant difference (~1500 kg/ha) in the final yields between the two starting at 75%. Simulations for the 2000 season follow the patterns found in the irrigated 1999 treatments with the highest yields (~9000 kg/ha enhanced, ~6000 kg/ha ambient) occurring at 125%. A larger difference (~1000 kg/ha) between the yields for the two CO2 treatments can be seen starting at 50%, which was the case with the non-irrigated versions of the 1999 treatments. This suggests that a correlation between radiation levels and lack of irrigation may exist.

The importance of irrigation is clearer in the precipitation level treatments on figure 6 where the irrigated 1999 simulations show little change in final yields compared to the non-irrigated ones in 1999 and 2000. The irrigated (schedule and amounts from field experiment data) 1999 ambient CO_2 simulation is steady at ~6000 kg/ha for all precipitation values except at 0% of the observed. The 1999 enhanced is steady at ~8000 kg/ha for all simulations except at 0% with a steady gap of 2000 kg/ha separating it from advanced and 1000 kg/ha respectively. Non-irrigated simulations for 1999 show a gradual increase with higher precipitation values due to the dry observed season with differences ranging from ~500 kg/ha at 25% to ~1000 kg/ha for precipitation values above 75% and maxing out at 150% (~6000 kg/ha enhanced, 4000 kg/ha ambient).

The 2000 season shows a linear rise in yields from 0% to 75% and is steady thereafter at slightly less than 8000 kg/ha for enhanced and ~6000 kg/ha for ambient. This could be explained by the way the model treats precipitation inputs in that once it has reached a certain level it ceases to incur any effect on the crop. Ambient and enhanced values differed by about 2000 kg/ha starting at 50% observed precipitation and steady thereafter.

Changes in the seasonal temperature from the observed (25°C in 1999 and 26°C in 2000) were also employed in this study to analyze its potential impacts on final yield by varying in a ±4 range. Figure 7 shows that the temperature effects were non-linear for all treatments. The 1999 irrigated, enhanced CO_2 has a significant climax (~8000 kg/ha) between 24°C and 26°C that may be attributed to temperature- CO_2 interaction, while the ambient gradually peaks at 25°C with a final yield between 6500 and 7000 kg/ha and varies a relatively small amount (<1000 kg/ha) for all temperature simulations. There were gradual decreases in yield for non-irrigated 1999 simulations as the seasonal average temperature rose beyond 23°C, with the final yield reaching around 6000 kg/ha for enhanced and 4000 kg/ha for ambient. This could be due to plant development being pushed to a later date by cooler temperatures and vice versa. The 2000 ambient and enhanced simulations show low yields at 22°C that rapidly increased at 23°C with small peaks (~8000 kg/ha enhanced, ~6000 kg/ha ambient) and a steady decrease thereafter. Inspecting Figure 2 we find that this pronounced response by the crops in 2000 may be due to a hard freeze at the end of the period and a slower development due to cooler temperatures in the beginning of the season. This, compounded with changes to the timing of precipitation due to a change in growth patterns could be the cause[*].

2.3.4 Simultaneous Climate Variable Changes

The individual climate variable simulations allowed us to identify various features associated with changes in the seasonal values of temperature, precipitation, and radiation on soybean yields. We extended our study to investigate how simultaneous changes in these variables would affect their impact. In order to elucidate how the magnitude of changes could be dependant on specific variable interactions, we extracted these relationships by way of factor separation (Stein and Alpert, 1993).

Figures 8 and 9 portray these variable interactions with the following information (as

* See appendix section 6.6

described in section 2.3): (a) direct effect of individual variable changes-given as E_R, E_T, and E_P; (b) the effect of interactions between two variables (e.g. temperature and precipitation varying simultaneously)-given as E_{RT}, E_{PT}, and E_{RP} and (c) the combined effect of all three variables simultaneously affecting the crop system-given as E_{RPT} (cf. Eq 1).

Figure 8 shows the factor separation plot for 1999 soy crop differential yield (kg/ha). The enhanced (irrigated) simulation sees the highest impacts on final yield by the radiation/precipitation (E_{RP}) and radiation/temperature (E_{RT}) interactions for enhanced CO_2 conditions. Ambient conditions had negative contributions from E_{RP} and E_{RT}, while E_{RTP} was the opposite of these two. E_R is only positive for irrigated ambient, which could be due to the relationship between available water and CO_2 concentrations in the atmosphere. The triple interaction E_{RTP} suggests how temperature changes can antagonistically interact with the dominant radiation-precipitation interaction regardless of CO_2 levels or irrigation. We must note that the factor separation used the mRmPmT set as the background and thus the relative effects of increases in precipitation may be different from that of the control run itself.

There is a significant difference in the direct effect of radiation alone (E_R), where higher levels aid crop growth of the ambient, irrigated treatment. This could be due to the general lack of water stress in an irrigated environment and its positive effects are supported by the way the E_{RP} generally gives higher yields. This indicates that lower radiation values could aid crop growth, and this can be further enhanced by higher precipitation and lower temperature values. This is not true when water stress is present regardless of CO_2 concentration. Interestingly, E_R shows a higher amount of CO_2 has a negative impact in non-irrigated conditions that point to an antagonistic effect.

The outcome of water stress is clearly seen when the direct effect of precipitation (E_P) is analyzed. Here, we see that the non-irrigated treatments react positively to higher levels of precipitation regardless of CO_2 concentration, whereas higher precipitation levels have very little effect when irrigation has taken place. Enhanced irrigated conditions do see a slight negative impact, pointing to a specific interaction with higher levels of CO_2. A combination of precipitation and temperature changes (E_{PT}) affects irrigated treatments positively and more so for ambient CO_2 conditions. Non-irrigated treatments show no discernable effect. Such an outcome could mean that a rise in temperature and precipitation would not affect the crop as much in an elevated CO_2 environment when there is an absence of water stress. A rise in temperature (E_T) alone seems to negatively affect all simulations except for ambient non-irrigated, this shows a general preference for cooler conditions by the crop.

The year 2000 (figure 9) shows different trends in contribution by direct effects of variables and their interactions although there is some common ground between them at times. Unlike 1999, the radiation/precipitation interaction (E_{RP}) had the highest positive contribution to crop growth when CO_2 for both ambient and enhanced CO_2 conditions, thus affirming how specific seasons tend to have different outcomes. The E_{RT} interaction is the has the lowest values with enhanced CO_2 conditions experiencing the highest negative impact. The E_{PT} interaction behaves the same as irrigated CO_2 enhanced conditions in 1999, albeit with higher contributions.

The triple variable interaction (E_{RTP}) has significantly positive numbers for both ambient and enhanced CO_2 concentrations. The effects are very different from 1999 where the enhanced condtions have switched signs. Ambient concentrations are comparable to those in 1999, however. This shows how the possible ameliorating effects of a rise in CO_2 levels can differ from season to season. Contributions to crop yield by radiation (E_R) have a noticeable negative impact for both CO_2 treatments. This suggests a preference for lower radiation values that can be further enhanced by higher precipitation values. The direct contribution by precipitation alone (E_P) shows an interesting relationship between water and CO_2. Both CO_2 treatments experience negative effects with higher precipitation. Since all conditions for the 2000 treatments were identical except for CO_2, we assume that interactions between water balance and the greenhouse gas could hold the explanation. Temperature (E_T) effects seem to follow the same trend, where warmer conditions result in a significant negative outcome for the yield. This holds true for both 1999 and 2000.

2.4 Conclusions

Our first step in this study was to test the CROPGRO model against observed data from Booker et al. (2005) for ambient and enhanced CO_2 conditions. After several calibration procedures for this experiment were undertaken, the more appropriate one led to more accurate representations of simulated yield and partitioning response to ambient conditions in the 1999 and 2000 seasons. Predicted variables for enhanced conditions in 2000 were also fairly accurate. Values for the 1999 season were underestimated but are within satisfactory levels. The simulations for the 2000 season are much more accurate and this may be due to specific conditions on that particular season that were better represented in the model. This, however, is open to conjecture.

After model validation, we developed sensitivity and interaction analyses for climate variables on soybean crop yield. Our results show nonlinear effects by solar radiation on final yields. Unlike previous studies (Roderick and Farquhar 2001, Niyogi et al. 2004, Mera et al.

2006), higher radiation values (125% for 1999 irrigated treatments and both 2000 season treatments) give way to higher final yields in the sensitivity analysis. Only the non-irrigated simulations in 1999 preferred lower amounts of radiation (75%-100% for maximum yields) suggesting how crops in water-stressed conditions may favor partly cloudy or hazy days in which the plants could react positively with an increase in yield as a result of diffuse radiation (Roderick and Farquhar 2001, Niyogi et al. 2004, Mera et al. 2006).

The factor separation isolated the role of radiation and yields negative effects for all simulations except the irrigated ambient in 1999. The part that radiation played in crop growth depended on the weather conditions experienced. Additional CO_2 changed the role of radiation in 1999, where the large positive numbers are experienced by irrigated treatments while enhanced non-irrigated showed a marked negative impact. This is contradicted by the results from 2000, where the negative effects of super-ambient radiation were negative for both CO_2 treatments. It is reasonable to suspect that other interactions may be taking place in a season-specific manner when radiation levels are changed.

Precipitation changes were not as dominant in our sensitivity study in terms of changing crop yields when irrigation takes place (1999) or when the season has been wet (2000). The opposite is seen for water-stressed conditions. The individual contribution shows slightly negative effects when the crop has been irrigated, with enhanced conditions giving more negative values. The role of CO_2 is positive when there is a lack of irrigation as seen with the 1999 non-irrigated and 2000 treatments. Past studies indicate that although the absolute amount of dry matter produced decreases at all CO_2 concentrations as water availability is reduced, the *relative* effect of increasing CO_2 on plant growth is enhanced with decreasing water supply (Morrison, 1993).

Temperature is another factor that has been shown to have significant effects on crop productivity (Boote et al., 2001; Fiscus et al., 1997). We chose a range of mean seasonal temperatures (±4°C) to analyze its direct effect on final yields. Crop responses were significant and varied according to water stress and CO_2 concentration scenarios. For instance, non-irrigated crops preferred cooler environments in order to reach higher yields, while irrigated fields performed best under the observed temperature (25 in 1999 and 26 in 2000). CO_2 increased yields dramatically for all simulations (>1000 kg/ha). The enhanced 1999 simulations responded differently according to irrigation, with a much higher difference in yield at 25 and 26 and next to none in warmer temperatures. All simulations were affected negatively by warmer weather as has been predicted in previous studies (Magrín et al., 2002; Boote et al., 2001; Maytín et al., 1995; Brown and Rosenberg, 1997).

The relative effects of increased temperature differs when coupled with simultaneous changes in other variables. For instance, E_{RT} suggests higher amounts of radiation and temperature would decrease yield in all simulations except for the enhanced CO_2 ones in 1999. Additional amounts of precipitation in warmer weather (E_{PT}) aided crop growth for irrigated treatments in 1999 and for both CO_2 treatments in 2000. Simulations experiencing water stress saw no benefit from the interaction, with ambient CO_2 concentrations having appreciably negative contributions. The direct effects of temperature in the factor separation analysis yields negative values for all treatments and is in agreement with the individual sensitivity tests and supported by findings in Mera et al. (2006).

The results in this study illustrate how multiple factors: solar radiation, precipitation, and temperature, potentially altered in a changed climate, could interact with each other in order to either reduce, or enhance the growth and physiological response for crops such as soybean in different water stress conditions and CO_2 concentrations. Certain aspects of these interactions differ greatly from season to season, as is the case with E_{RP} and E_{RT}, where contributions by these interactions show opposite numbers between the two seasons.

An important conclusion of the interaction-based study is that effect of an individual variable change would depend on the changes occurring in other variables within the earth system, and that these variable interactions have significantly diverse outcomes when plants are exposed to irrigation or changes in atmospheric concentrations of CO_2. This has important implications in determining the vulnerability of agriculture for projected climate change scenarios, and in the development of dynamical land surface models that use crop modeling systems within their system The inclusion of elevated CO_2 and irrigated and non-irrigated field conditions offers a more complete picture of how future climate may influence crops.

Individual variable change based sensitivity and impact evaluation identifies the magnitude of effects on the crop yields in various initial conditions such as CO_2 concentration and irrigation choices. The multiple parameter change portion of this study indicates the crop yields and other impacts have different vulnerabilities (sensitivities) as compared to a single variable study in CO_2 enrichment and water-stress treatments. Therefore, future climate impact research should consider assessments based on ensemble analysis, in addition to the sensitivity scenarios, to synthesize the feedbacks to explicitly identify the interactions between the variables in different seasonal conditions (multiple years) as well as atmospheric composition and approaches to irrigation. For instance, the current CO_2 enrichment crop model studies do not include other variables of air quality, such as ozone, that have been proven to have significant effects on plants (Heagle et al., 1999;

Booker et al., 2005). There is a need for such variables to be included in the model in order to properly identify possible outcomes that may arise due to climate change. This, in addition to the inclusion of multi-parameter analysis in future studies, may aid in providing a more complete picture of the earth system and present useful information for the use of crop modeling within dynamical land surface models.

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Table 1. Definition of variables in multiple interaction simulations.

Expt	Variable Setting
mRmPmT	50% rad., 50% precip., -2C temp.
pRmPmT	150% rad., 50% precip., -2C temp.
mRpPmT	50% rad., 150% precip., -2C temp.
mRmPpT	50% rad., 50% precip., +2C temp.
pRpPmT	150% rad., 150% precip., -2C temp.
pRmPpT	150% rad., 50% precip., +2C temp.
mRpPpT	50% rad., 150% precip., +2C temp.
pRpPpT	150% rad., 150% precip., +2C temp.

Table 2. Average seasonal and monthly weather conditions and CO_2 concentrations. Temperature is in daytime averages and CO_2 concentrations are 12 h d_1 (0800–2000 h) averages.

Parameter	*Year*	*June*	*July*	*Aug.*	*Sept.*	*Oct. 1-16*	*Season*
Temp., °C	1999	24	28	28	22	21	25
	2000	28	28	28	24	21	26
Rain, mm	1999	50	60	80	460	10	660
	2000	170	90	160	230	0	650
Solar Rad. (MJ m-2)	1999	20	20	19	14	13	17
	2000	21	19	18	14	13	17
[CO2], μmol mol^{-1}							
Ambient	1999	380	366	370	372	386	373
Enhanced	2000	659	703	737	689	688	699
Ambient	1999	368	361	365	373	376	369
Enhanced	2000	700	764	730	714	686	717

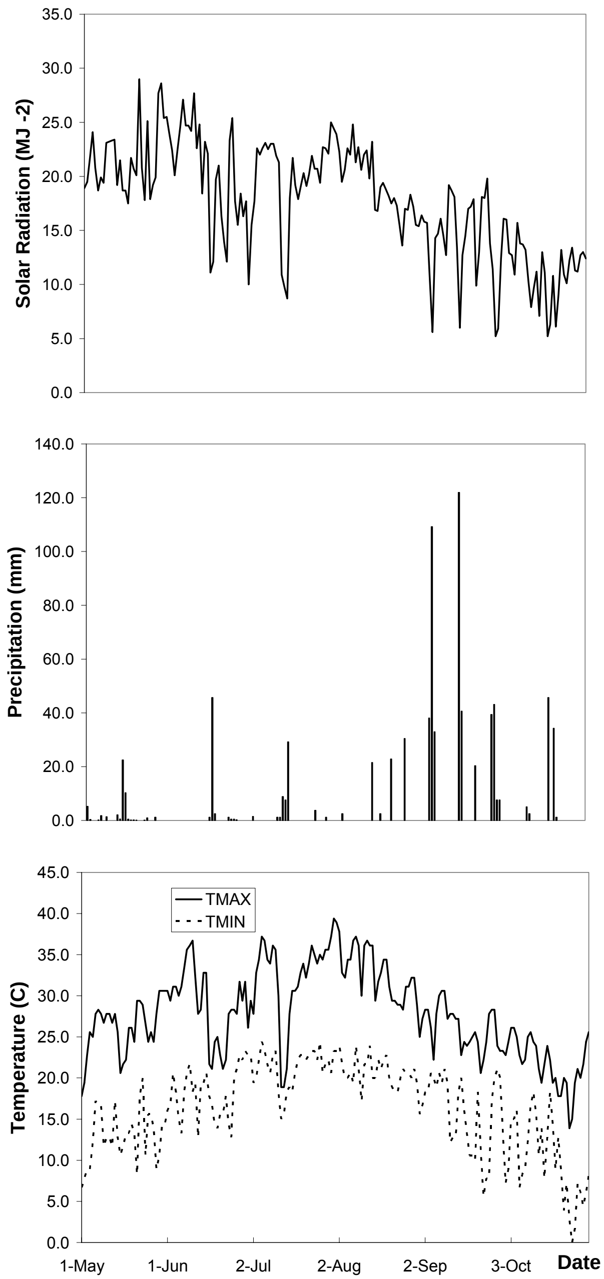

Figure1: Observed climate data for the 1999 season. Solar radiation (MJ m-2 day-1) shown in the top plot, precipitation (rain – mm) in the middle, and Max. temp. (°C) (solid line), min. (dashed line) in the bottom plot.

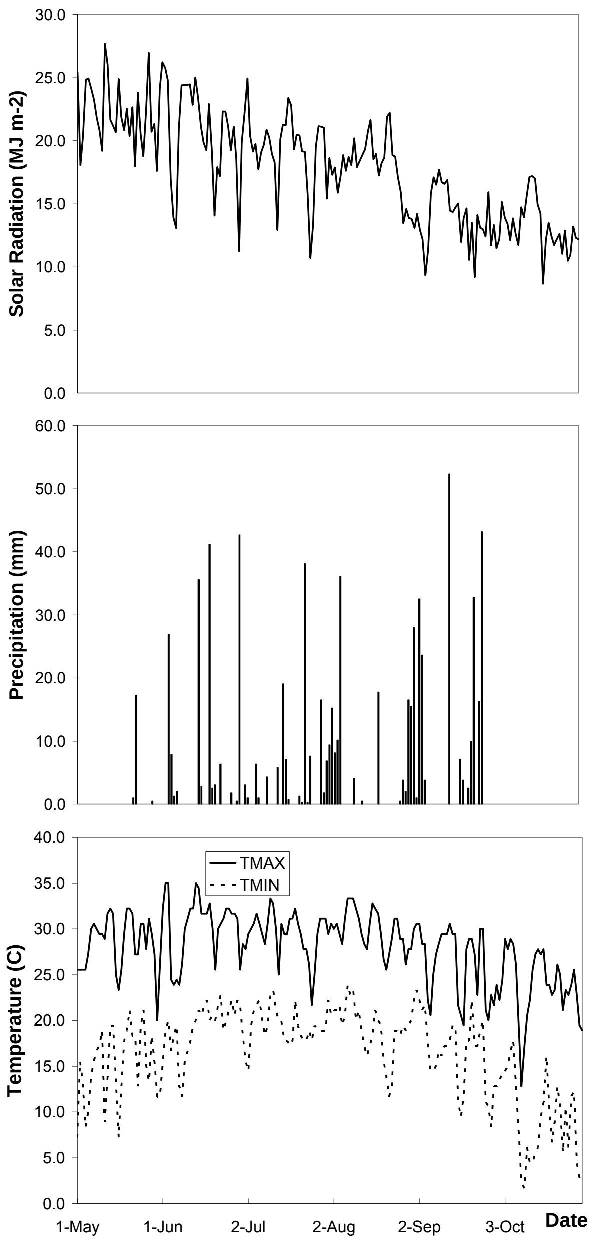

Figure2: Observed climate data for the 2000 season. Solar radiation (MJ m-2 day-1) shown in the top plot, precipitation (rain – mm) in the middle, and Max. temp. (°C) (solid line), min. (dashed line) in the bottom plot.

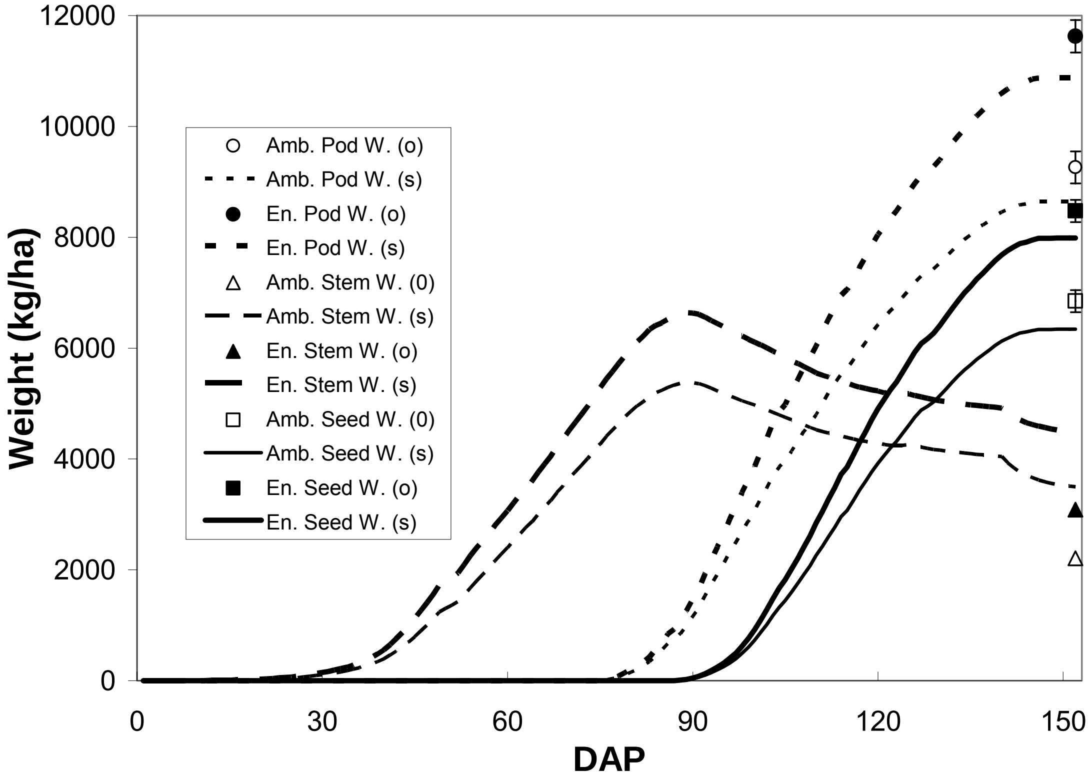

Figure3: Predicted (lines) versus observed (points) partitioning masses (pod, stem and seed) in 1999. Error bars indicate the confidence intervals in the field experiment.

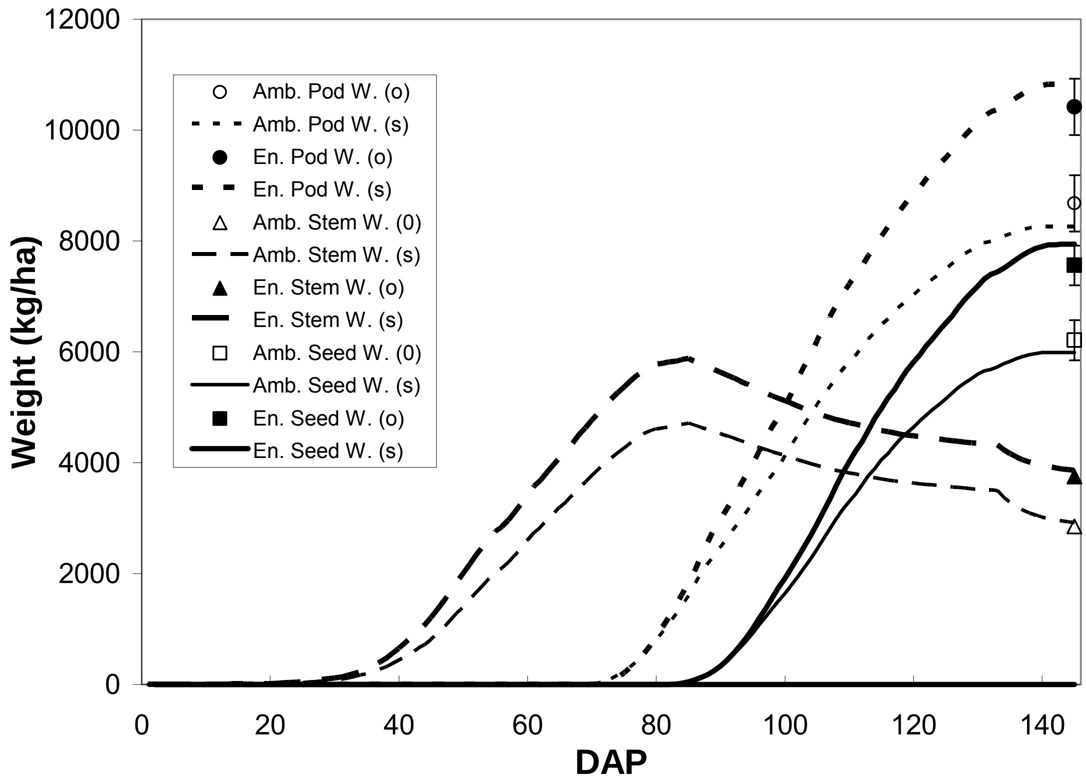

Figure 4. Same as fig. 3 but for 2000.

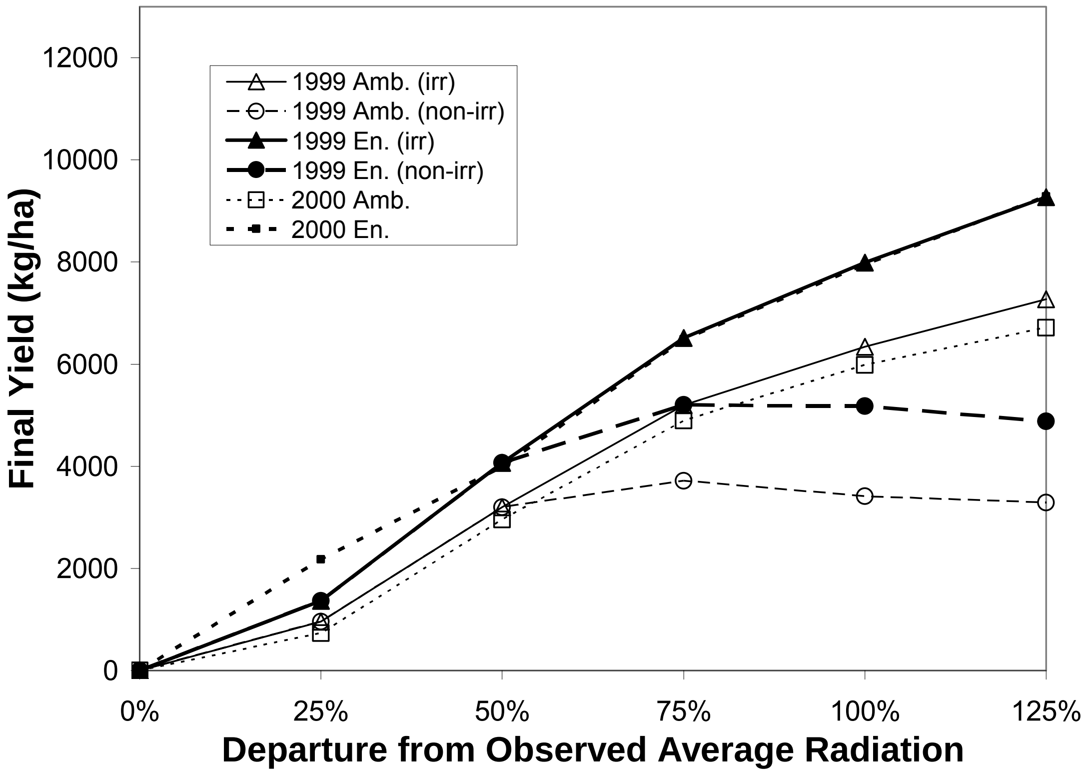

Figure 5. Non-linear effects of ambient and enhanced CO_2 in irrigated and non-irrigated environments for 1999 and ambient and enhanced CO_2 for 2000. 1999 ambient and enhanced irrigated simulations have a higher yield at 125% while non-irr. versions are higher between 75 and 100%. The year 2000 simulations seem to prefer radiation levels at 125% for both ambient and enhanced CO_2 conditions.

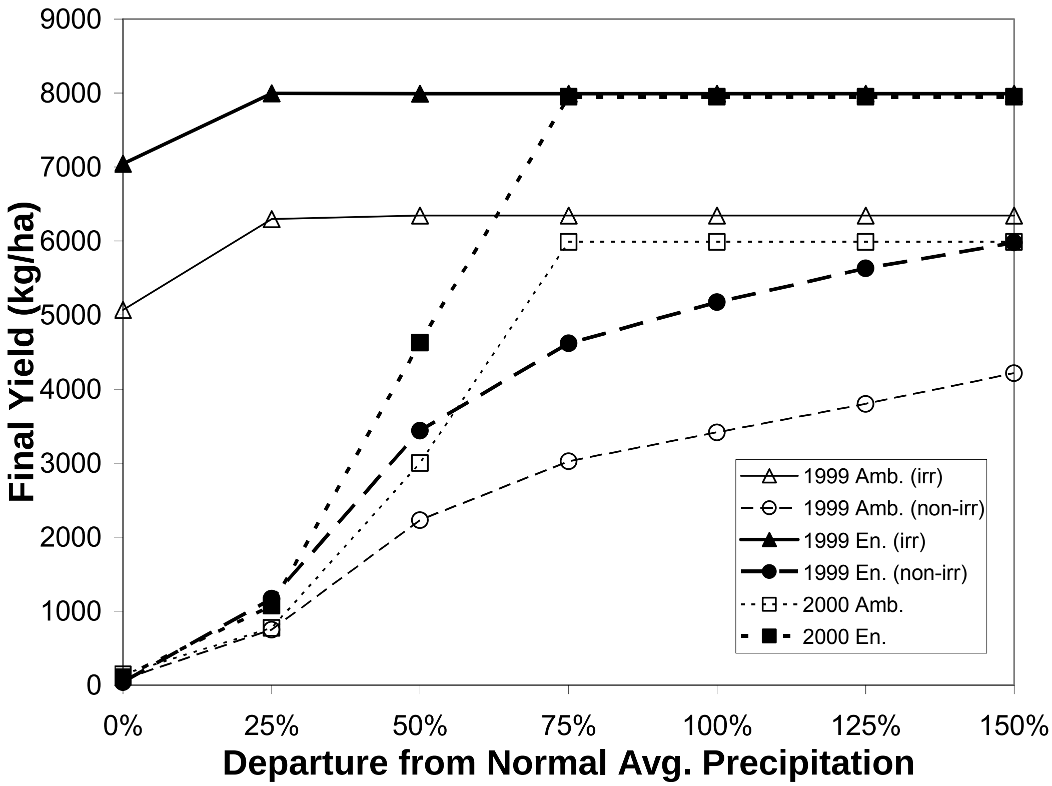

Figure 6 Same as Fig. 5 but for precipitation changes. The relationship is non-linear for the 1999 enhanced CO2 treatments and for both ambient and enhanced treatments in 2000. The plots shows water stress as seen when irrigated treatments in 1999 are compared to the non-irrigated..

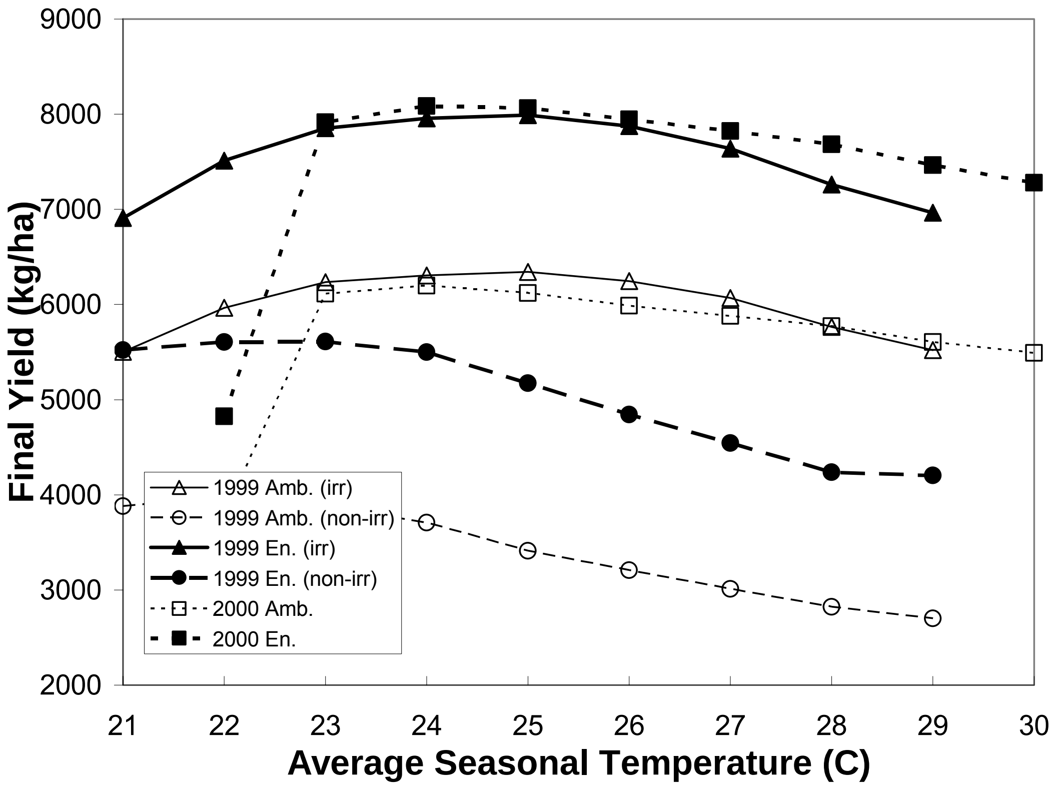

Figure 7. Same as fig. 5 but for changes in temperature. The effects are non-linear with gradual decreases in yield for non-irrigated 1999 simulations. The 1999 irrigated, enhanced CO_2 has a significant peak between 24°C and 26°C, while the ambient gradually peaks at 25°C. The 2000 ambient and enhanced simulations show low yields at 22 that rapidly increase at 23 with small peaks and a gradual decrease thereafter.

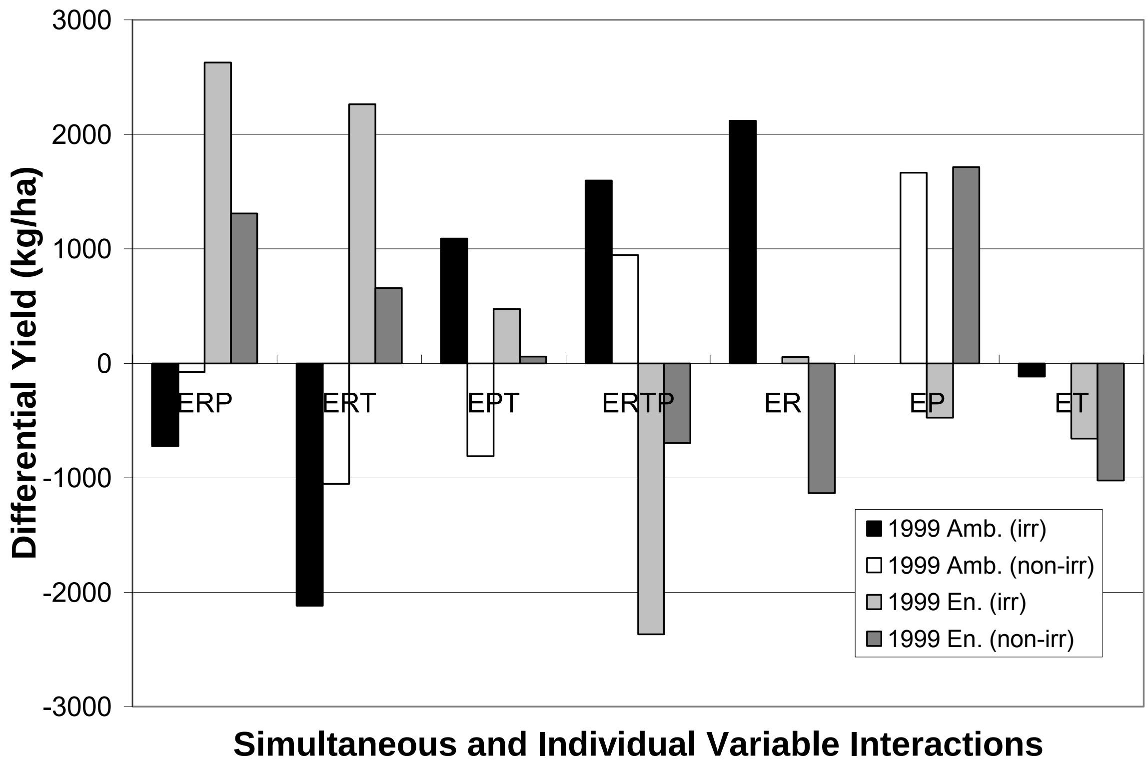

Figure 8 Factor Separation Plot for 1999 Soy Crop Differential Yield (kg/ha). The enhanced (irr) simulation sees the highest impacts by the radiation/precip. (E_{RP}) and radiation/temp (E_{RT}) interactions, while it is negatively affected by the triple interaction (E_{RTP}). All simulations follow a similar pattern in positive effects (E_{RP}, E_{RT}) and negative (E_T, E_{RTP}) but differ in opposite manners when irrigation is changed for E_{PT} and E_P. E_R is only positive for irrigated ambient.

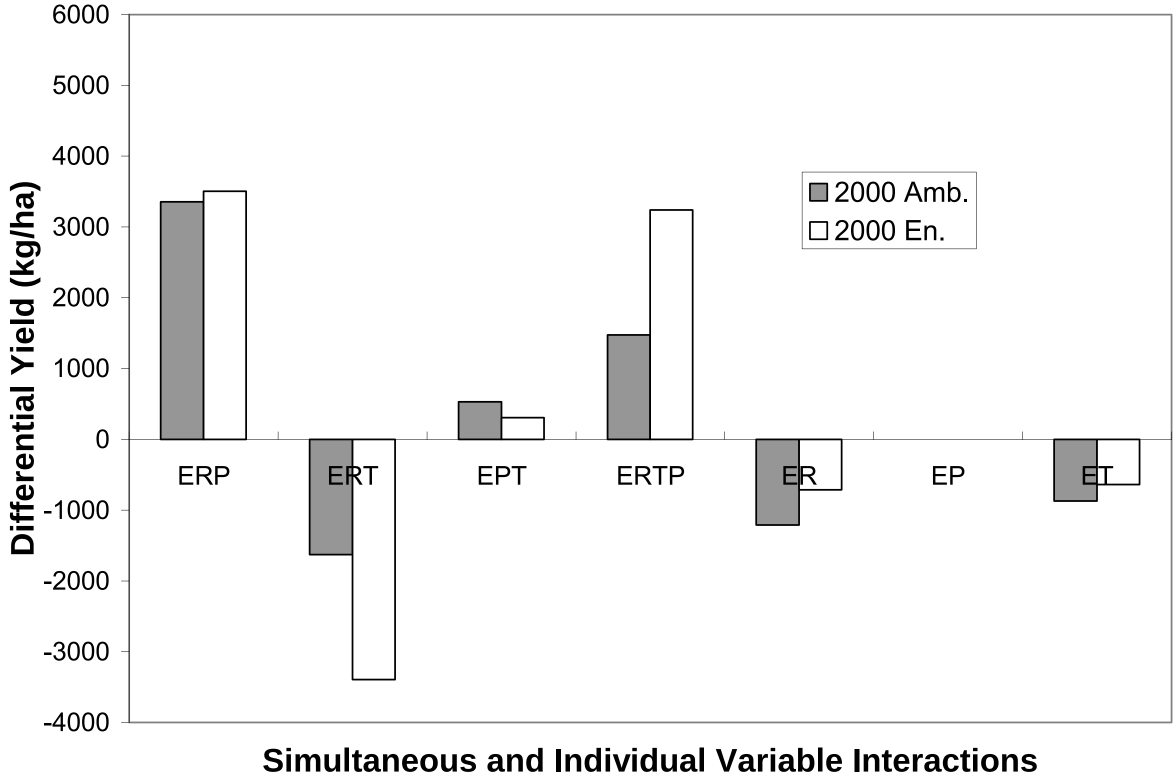

Figure 9. Same as figure 8 but for the 2000 season The enhanced (irr) simulation sees the highest impacts by the radiation/precip. (E_{RP}) and radiation/temp (E_{RT}) interactions, while it is negatively affected by the triple interaction (E_{RTP}). All simulations follow a similar pattern in positive effects (E_{RP}, E_{RT}) and negative (E_R, E_{RTP}) but differ in opposite manners for E_{PT}, E_P and E_T, pointing to an interaction with higher levels of CO_2.

3. The Effect of Environmental Forcing on Improving Dynamical Land Surface Models: An Agrotechnology Model Based Study

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Abstract

Climate models have often been used to drive crop model simulations to discern crop responses to climate change. Recent advances in regional climate models (RCM) using more finite scales have the potential to improve the quality and suitability of data to be used in crop models for future projections. In this study we use the model CROPGRO to analyze responses to climate data provided by the RCM for data derived from the *A2* emission scenario simulation. We have developed anomalies to circumvent the effects of model bias and noise at the local agricultural scale. The crop model was driven by observed weather data from a station south of Raleigh, NC (35.8N, 78.6W), original RCM output, and calculated anomalies for the years 1962 through 1989. Observed and anomaly simulations were carried out in four different carbon dioxide (CO_2) levels: observed 1989 and transient 1962-1989, and International Panel on Climate Change (IPCC) *A2* emission scenario for 2099 and transient 2072-2099. We used default CROPGRO CO_2 levels to drive the original RCM output for comparison with enhanced 2099 levels. Results indicate that the calculated model anomalies were useful in regaining natural precipitation variability and lessening overestimated rainfall, which allowed CROPGRO to provide better representation of crop responses. We found that the contribution of precipitation to the variance in yields calculated

from the observed climate was appreciably higher than the anomalies, suggesting that precipitation levels were not at an optimum level for proper CROPGRO simulation. Temperature contributions to crop yields were higher in the anomalies and original RCM data, indicating that the warming trend found in the *A2* simulations had direct negative effects on the modeled soybean crops. Enhanced levels of CO_2 proved beneficial in all simulations by reducing the negative impact of low soil moisture. Its influence on the anomalously high RCM temperatures was negligible. Future studies should consider alternate ways to calculate the anomalies to attain a better representation of how future climate projections may affect crops. Further, the analysis of evapotranspiration and photosynthesis should be included to discern agricultural feedbacks that may affect the atmosphere, thus providing a basis for improving dynamical land surface models and additional testing of crop model response.

3.1 Introduction

Climate models are increasingly being used in concert with crop models to analyze the potential effects that climate change may have on agriculture. A wide range of simulation studies has focused on the potential effects of climate change on soybean productivity (Pickering et al., 1993; Hansen et al., 1996; Ogoshi et al., 1998; Boote et al., 2001; Deepak and Agrawal, 2001; Booker et al., 2005). The CROPGRO-Soybean model (Jones et al., 2003) and its precursor, SOYGRO (Jones et al., 1989; Wilkerson et al., 1983), have been used in many of these simulation experiments and have also been extensively evaluated in field trials worldwide (Ogoshi et al., 1998; Wang et al., 2001; others). Several studies have been performed to parameterize and validate these models for simulation of soybean growth under North Carolina conditions (Boote et al., 1997; Mavromatis et al., 2002; Mera et al., 2006a, b; Welch et al., 2002).

Future climatic scenarios derived from General Circulation Models (GCMs) have been utilized on global scales to address world food production and its economic impact (Rosenzweig and Parry, 1994; Fischer et al., 1995; Parry et al., 1998; IPCC, 1998). Data from GCMs have been applied to meteorological measured data to be used as inputs for crop models (Matthews et al., 1995; Jinghua and Erda, 1996; Feddema, 1999; Mearns et al., 1999; Alexandrov and Hoogenboom, 2000; Guerreña et al., 2001; Alexandrov et al, 2002; Southworth et al., 2002). These models, however, lack the resolution to discern patterns in local and regional climates (Gates, 1985; Smith and Tirpak, 1989; Cohen, 1990; Giorgi, 1990; Grotch and MacCracken, 1991; Lane et al., 2000).

Statistical models have been employed in order to downscale GCM simulations to generate climate scenarios on a finer scale, but have shown important drawbacks such as the question of maintaining the same statistical algorithms between climate variables under a future climate (Wigley et al., 1990). Regional climate models (RCMs) have been favored due to their potential ability to enhance spatial and temporal differences in crop performance through higher resolution (Semenov and Jamieson, 2000; Cocke and LaRow, 2001; Guerreña et al., 2001).

The RCM's ability to approximate regional and local climate change scenarios allows for its use in predicting impacts on agriculture (Giorgi et al., 2001; Hanley et al., 2002). A number of regional models have been applied throughout the world to analyze crop sensitivities to changes in weather patterns and rising levels of CO_2 (Guerreña et al., 2001; Hanley et al., 2002; Adams et al., 2003; Carbone et al., 2003; Tsvetsinskaya et al., 2003). Although RCMs have relatively coarse resolution compared to the fine-scale data requirements of crop models, coupling of the two can present relevant information for agricultural decision makers (Hanley et al., 2002).

Current and future work on advancing climate modeling science is aimed at creating finer scales that lend themselves to applications such as agriculture as well as improving dynamical land surface models (Druyan et al., 2001; Goddard et al., 2001; Challinor et al., 2003). A recent study applied high model resolution to capture fine scale processes, and discern their effect on regional and local responses to large-scale changes brought about by anthropogenic and non-anthropogenic causes (Diffenbaugh et al., 2005).

We believe that utilizing output from a regional climate model to drive a crop simulation model will aid in the development and improvement of dynamical land surface models by testing the response of a crop model to climate information derived from an RCM. The objectives of this study were to (i) develop model anomalies to use as input in

CROPGRO, (ii) diagnose the effects of climate change on regional productivity and (iii) identify possible improvements for the integration of crop models within a dynamical land surface modeling system.

Methodology and descriptions of the regional climate model and crop model will be discussed in section 2. Section 3 will present our results and discussion. Our conclusions will be given in section 4.

3.2 Methodology

Our overall approach in this study was to generate daily weather data using an RCM by developing model anomalies. We analyzed precipitation and temperature trends for observed weather, model anomalies, and original RCM model scenarios in order to get a better understanding of crop reactions to the environmental conditions used in this study, We then used output from the RCM as input to a soybean crop model to identify the crop model's response and diagnose the effects of future climate projections from the RCM.

3.2.1 Regional Climate Model

In this study we used RCM output from model runs used in Diffenbaugh et al. (2005) to generate daily weather data (min/max temperature, total precipitation) for the study site (Raleigh, NC). The weather data generated for two time periods: the reference integration (*RF*) years, 1962-1989, and a future integration (*A2*) period, 2072-2099 using the Abdus Salam Institute for Theoretical Physics Regional Climate Model, Version 3 (RegCM3) (Pal et al., 2000; Giorgi et al., 2003a,b. In this study, we used simulated weather data for one grid point (35.69°N, 78.84°W) from the model grid described by Diffenbaugh et al. (2005).The

RegCM3 used Atmospheric boundary conditions provided by the National Aeronautics and Space Administration (NASA) Finite Volume General Circulation Model (FV-GCM) (Atlas et al., 2005). Sea surface temperatures (SSTs), required as input for the RCM,were derived from the Hadley Centre HadCM3 coupled atmosphere–ocean GCM (Johns et al., 2003). The global model was run at 1° latitude × 1.25° longitude horizontal resolution with 18 vertical levels. Solar radiation was calculated from the minimum and maximum daily temperatures using mechanistic model equations (Hargreaves and Samani, 1986).

3.2.2 Crop Model

The CROPGRO-Soybean model (Jones et al., 2003) was used to examine soybean [*Glycene Max*] responses to observed and simulated weather data. CROPGRO is a process based model that calculates physical, chemical, and biological processes in the plant and the environment and belongs to the DSSAT (Decision Support System for Agrotechnology Transfer). DSSAT (Hoogenboom et al, 2003) combines crop soil and weather data bases and programs to manage them, with crop models and application programs, to simulate multi-year outcomes of crop management strategies. The model simulates plant response to soil, weather, water stress, and management. Site specific input data are used to calculate growth, development, and partitioning processes, from planting to the predicted harvest maturity. Growth is integrated at a daily time step, predicting biomass accumulation in vegetative and reproductive structures, leaf area, and yield. CROPGRO calculates plant carbon balance, crop and soil N balances, and soil water balance (Boote et al., 1998). Crop phenological development in CROPGRO is sensitive to water deficit, temperature, photoperiod, and N stresses, and is expressed as physiological days per calendar day (PD/day).

CROPGRO simulates elevated CO_2 effects on photosynthesis and evapotranspiration (Alagarswamy et al., 2006; Boote and Pickering, 1994; Tsuji et al., 1998). The ability of CROPGRO to evaluate potential effects of [CO_2] on soybean photosynthesis and productivity using default photosynthesis equations has been confirmed with a Willmott's index of agreement ranged from 0.86 to 0.99 (Alafarswamy et al., 2006). Evapotranspiration (ET) calculation uses the ratio of transpiration in a CO_2 enriched atmosphere to that in ambient conditions to account for the effect of elevated CO_2 on stomatal closure, increased leaf area index, and potential transpiration. Leaf resistance is computed as a function of prescribed CO_2 levels. The ratio procedure gives a lower transpiration rate per unit leaf area for increased CO_2 concentrations on a daily basis. Seasonal evapotranspiration, however, may not change proportionally, and may actually be augmented due to higher biomass and the greater leaf area produced in an enriched CO_2 atmosphere (Tsuji et al., 1998). In the model, ET was derived using the Priestley-Taylor method (Priestley and Taylor, 1972).

We made the following assumptions for the soybean crop. The soil used was Norfolk Sandy Clay Loam; the cultivar was ESSEX-NCSU (5); the planting date for all simulated years occurred on May 15th; plant population was set at 25 plants m^{-2}; row spacing was set at 19cm with a depth of 3.5cm; no irrigation was taken into consideration and N availability was set at default.

3.2.3 Experimental Design

In order to assess the impact of climate change on soybean crops in North Carolina, we used output from the two model integrations, *RF* and *A2*. Observation data (*OBS*) for the years 1962-1989 were obtained from the National Weather Service office in Raleigh, NC. Model anomalies (*AN*) were computed using the following equation:.

$$(A2_{daily}-RF_{daily})+OBS_{daily}=AN_{daily} \tag{1}$$

where RF_{daily} represents daily weather values (total precipitation, total solar radiation, min/max temperatures) for *RF* and $A2_{daily}$ represents the respective values for *A2*. These differences were added on a daily basis to *OBS* values in order to lessen the effects of model biases such as overpredicted precipitation.

We ran CROPGRO using the observed weather data at the following CO_2 levels: transient 1962-1989 (315.2-354.5 μmol), 1989 (354.5 μmol), transient 2072-2099 (620-808.57 μmol), and 2099 (808.57 μmol). The annual time-varying concentrations of CO_2 for *RF* and the corresponding FV-GCM integration are from Schlesinger and Malyshev (2001). Transient CO_2 values for *A2* and the corresponding FV-GCM integration were obtained from years 2072–2099 of the Special Report on Emissions Scenarios *A2* scenario (IPCC 2001). Model anomalies were also applied to CROPGRO at the same CO_2 levels. Additional simulations were included using the original RCM data for *A2*. Specific items collected from the CROPGRO output include final yield, soil moisture, and effective precipitation. Average annual temperatures and total precipitation were retrieved from the weather file for each year for observations, future model predictions, and model anomalies. Final yield for all simulations was used as the primary variable employed for comparison with environmental conditions (temperature, precipitation, and soil moisture). Soil moisture was derived by averaging the initial soil moisture at the beginning of the growing season and the final at the end of the growing season as given by the crop model output. We calculated R^2 to determine the contribution of the environmental variables to the variance in yields. Interannual variations for all the types of simulations described above were also analyzed to detect patterns in the variability.

Due to the complexity of solar radiation and its corresponding equations, it was difficult to deduce an accurate measurement for the *AN* predictions. We decided to disregard the differences in *A2* and *RF* and used the solar radiation calculated from the observed temperature values throughout the period. We must note that an increase in CO_2 concentrations, as well as other greenhouse gases like methane, could have a more significant effect on atmospheric absorption of total solar radiation than that of photosinthetically active radiation (PAR) (Oke, 1987; Tsubo and Waker, 2003). Reflection of both could be augmented with increases in these gases as well as water vapor. This could lead to a lower amount of both total solar radiation and PAR, with PAR being affected more. The ratio of diffuse to direct solar radiation may also increase.

3.3. Results and Discussion

3.3.1 Climate: Observed, Model, and Model Anomalies

The observed climate for the 1962-1989 time period is shown in Figure 1. Crop yields are likely to be most affected by precipitation variability. The peaks and valleys in the annual precipitation totals (mm) may be considered as proxies for soybean production on a yearly basis. It is important to note the range in total growing season precipitation (~300-800 mm) in order to compare with raw model output and model anomalies. There did not seem to be a marked overall trend, although precipitation patterns seemed to have relatively less variability in the early to mid 1970s. Temperature (°C) is also an important variable to consider in the analysis since it affects plant development. The figure shows a more variable pattern for the latter 3rd of the period with a significantly lower value in 1983.

The growing season precipitation and temperature patterns were derived from the *A2* portion of the RCM simulation to analyze their impact on possible future trends in soybean production (Figure 2). *A2* precipitation predicted by the RCM tended to be twice the amount of *OBS?* with a range of 1300 mm to 2300 mm. This is likely due to model biases since anomalously high rainfall was also present in the *RF* (not plotted). Interannual variability was higher at the beginning of the period with a gradual dampening in the second half. There also seemed to be a slight downward trend coupled with the decrease in variability. Temperature had a marked upward trend with average annual values exceeding 18°C closer to the end of the period. This, along with the relative decrease in precipitation would tend to negatively affect soybean yields.

Model anomalies (*AN*), calculated to obtain a better representation of natural variability, are plotted in Figure 3 to show patterns in rainfall and temperature. The implementation of *AN* reduced model biases by decreasing total annual precipitation. Values ranged from ~500 mm to ~1800, thus cutting precipitation by half. The year 1969 could be treated as an outlier because of the anomalously high rainfall totals (~2500 mm), which upon closer inspection, were found to have originated in the *RF*. Interannual variability also resembles more natural patterns. The model anomalies tended to create further biases in the temperatures due to the large differences in temperature ranges between *RF* and *A2*. The *AN* subsequently had considerably warmer temperatures than those predicted in *A2* after the calculated anomalies were added to *OBS*. For several years, average *AN* temperatures exceeded 20°C, thus surpassing predicted *A2* average temperatures. Still, more naturally variable patterns were achieved with *AN*. The warming trend present in *A2* was maintained, albeit at a smaller scale.

3.3.2 Interannual Crop Yield Patterns at Different CO_2 Levels

Crop simulations using the observed climate elucidate the year to year variability of soybean production based entirely on environmental conditions (daily precipitation, temperature, and solar radiation). Figure 4a shows the natural crop yield patterns for *OBS* at the default CO_2 level (330 µmol) and 1989 level (352.73 µmol). There is no distinction between the two simulations beyond the additions to the final yield incurred by increased CO_2 levels. For example, differences between the two CO_2 treatments vary between ~300 kg/ha for high yielding years to less than 50 kg/ha for years of low production. The comparison between the default CO_2 level and transient CO_2 level treatments (315-352.73 µmol) gave similar results, except here we can see how values below the default tend to cause lower yields to occur for the first half of the simulated years (Fig. 4b).

Treatments with elevated CO_2 levels were also simulated to analyze possible benefits of increasing levels of the greenhouse gas. Figure 4c presents annual yields at default CO_2 levels as well as the 2099 level (800.58 µmol) showing the dramatic increase in yields, following the same variability patterns. Yields from transient *A2* level simulations do not differ much from those from the 2099 treatments beyond the proportionality of CO_2 enrichment and its eventual positive influence on yields (Fig. 4d). There is an overall linear increase in the final yields as was observed in Figure 2, as CO_2 levels reach that of the 2099 treatment.

The results of simulations made using unmodified *A2* weather data and two CO_2 levels (default and 2099) are shown in Figure 5. Overall, yields from these simulations lack the range in variability present when observed climate data are used. In particular, fewer years had exceptionally low yields for either default or enhanced CO_2 treatments. In addition, enhanced CO_2 always resulted in substantial yield increases, whereas in simulations using observed weather data enhanced CO_2 did not always result in a yield increase (Figure 4d). Precipitation appears to be the limiting factor in very low-yielding years in simulations using observed weather data. High temperatures appear to be more important in low-yielding *A2* simulations in which precipitation levels were generally much higher (Figures 1 and 2). The downward trend in yield for both CO_2 levels in *A2* simulations reflects the upward trend in temperature (Figure 2).

Model anomalies, developed in order to circumvent the effects of possible model biases and provide more natural variability, gave some important results. The overall variability seen in *OBS* was restored as can be seen by the default CO_2 simulations in Figures 6a-6d. Like the *OBS*, the influence of higher CO_2 levels, as was the case with the 1989 level (Fig. 6a) was still present in the form of higher final yields. Transient 20th century levels of the gas also showed a clear picture of how yields increased somewhat linearly with rising levels of CO_2 (Fig. 6b). Figures 6c and 6d also showed patterns similar to those found in the *OBS* simulations.

The downward trend captured in the *A2* simulations was not present in *AN* due to the large variability during the earlier part of the period incurred by the addition of *OBS* to the anomalies. However, there are no clear high peaks in the second half of the simulated period, while the first half included at least 6 years that were higher than all yields in the latter half.

3.3.3 Variable contributions to variance in crop yield

a.) Observed Climate

Analysis of variable contributions to crop yields was important to determine how crops react to changes in environmental conditions in the model projected climate and the calculated anomalies. We first compared variable contributions in different CO_2 concentrations for *OBS*. The relationship between precipitation (mm) and crop yields (kg/ha) is shown at 1989 CO_2 level (Figure 7a), transient *RF* levels (Figure 7b), 2099 level (Figure 7c), and transient *A2* levels (Figure 7d). As expected, the relationship is linear with large R^2 values for all CO_2 treatments. Differences among treatment R^2 values were very slight (Figures 7a and 7c).

Temperature (°C) is a factor that differs in importance and effects on different species of plants. Figure 9a shows little relationship between crop yields and average yearly temperatures in a constant 1989 level of CO_2. The same is found with transient levels of the gas in the *RF* period, where there is no significant contribution by the variable (Fig. 8b). Similarly, higher levels of CO_2 in either steady 2099 CO_2 level or transient *A2* levels have very little impact in how temperature affects soybean crop development (Figs. 8c and 8d respectively).

b. *A2* Projected Climate

Future climate predictions for the projected emissions in *A2* gave interesting results in terms of trends and patterns in temperature and precipitation. Since the model contains significant biases (i.e. excessive rainfall/rainy days) at the subgrid scale employed in this study, we analyzed the *relative* effects that these patterns may have on soybean crops without removing biases.

Simulated yield showed low correlation with precipitation (mm), with an R^2 value of 0.09 for projected 2099 CO_2 concentrations and 0.12 for default levels of the gas (Fig. 9a). The slightly higher correlation between yield and precipitation for default levels of CO_2 could be explained by the increase in water use efficiency under high levels of CO_2. With simulated precipitation being so high, little water stress would be expected to occur in either CO_2 scenario, but slightly more could be expected under default levels than under elevated levels.

The case is different for the effects of temperature changes. The trend towards warmer temperatures seen in Figure 2 gains importance when compared with the interannual variability of yields using model projected climate (Fig. 5), for as temperatures rise, the yields tend to fall. Figure 9b shows this relationship in more detail, where it is seen that there is a clear negative correlation between temperatures and yields. The modeled soybean crops tend to prefer the cooler climates from the beginning of the *A2* period. Temperature's negative contribution to variance in the yields is almost the same for the default CO_2 concentrations (empty circles) and projected 2099 *A2* (solid squares), suggesting that the benefits of higher CO_2 levels may not be enough to ameliorate the negative effects of an increasingly warmer climate.

c. Model Anomaly derived Climate

The calculated *AN* helped diminish the influence of climate model noise by reducing precipitation amounts and rainy days to more natural levels. The results facilitate the evaluation of the crop model's responses to the RCM predicted climate. Precipitation is still not as much of a limiting factor to crop yields as it was in the observed climate treatments (Figs. 10a through 10d). The R^2 values of all CO_2 scenarios used were drastically lower (~0.34), with no significant differences between treatments. This suggests precipitation has a lesser degree of importance and could be explained by some of the higher precipitation years that were not reduced enough by the method chosen for anomaly derivation. We can observe this in the cluster of data points from about 800 to 1500 mm in figures 10a through 10d. This effect was also evident in the precipitation analysis for *A2* data (Fig. 9a), where abnormally high levels reduced the model's ability to provide realistic simulations.

Temperature contributions were negligible (Figs. 10a through 10d); suggesting that the slight warming trend found in figure 3 was not significant enough to negatively affect the crops to the extent that the *A2* model predictions had. Increased interannual variability in temperatures could also be another factor that reduced the contributions.

3.4. Conclusions

We have tested CROPGRO model response using model output from a RegCM3 simulation (daily precipitation, min/max temperatures) applied over the contiguous United States under the Special Report on Emissions Scenario *A2* emissions scenario, and run at a fine resolution to analyze finite scale impacts on large scale processes. Simulations utilizing *OBS* data had higher R^2 values between crop yields and precipitation, than did *A2* or *AN* scenario simulations. Conversely, temperature in *A2* had a significantly higher contribution to yield variability.

Interannual variability of average yearly temperatures and total precipitation was analyzed to discern patterns and possible trends in the data for *OBS*, *A2*, and *AN*. Simulations with the *A2* scenarios had significant warming trends and a rainfall pattern that tended to be drier near the end of the period. Precipitation was considerably over-estimated at two to three times the amount of the observed and abnormally high amount of rainy days within a one month period. The calculated *AN* did not retain the drying pattern but more natural variability was gained from the *OBS* data used in its calculation. The anomalies were able to reduce the amount of precipitation and rainy days, approaching a more realistic pattern that would be more applicable for crop modeling.

Direct analysis of crop responses to CO_2 concentration showed increased yields for higher amounts (Unsworth and Hogsett, 1996). For the majority of cases, there was negligible year to year variation in proportionality between default CO_2 conditions in CROPGRO and the various steady (1989, 2099) and transient (*A2*, *RF*) treatments for all scenarios (*OBS*, *A2*, *AN*). A handful of years in both the *A2* climate and *AN* simulations had clear differences in proportionality where the expected overall interannual pattern in the yields is not present. Higher concentrations CO_2 tend to incur changes in the variability present at default levels. More specific interactions between climate variables (i.e. precipitation-radiation, precipitation-temperature, etc.) or individual variable contributions could also play a role in determining how crop production could be affected at different levels of the greenhouse gas (Wolf, 2002; Alexandrov et al., 2002, Mera et al. 2006a,b). This is compounded by the possibility that PAR could be greatly affected by high amounts of greenhouse gasses (Tsubo and Walker, 2003), thus making any conjectures on this matter more complex.

Precipitation has been found to be the leading factor affecting crop yields, regardless of CO_2 concentrations (Rosenzweig and Tubiello, 1997; Iglesias et al., 1996; Ferris et al., 1999; Mera et al, 2006a). The variable contribution plots support this case for *OBS* and *AN* climate-based crop simulations. Here, precipitation is shown to have a strong linear relationship with crop yields, giving high R^2 (~0.74) values for all CO_2 treatments using *OBS* climate. This relationship is only moderately significant for *AN* ($R^2 \approx 0.34$) and relatively negligible for original *A2*. We must note, however, that simulations with the original *A2* climate indicated important differences between 1989 and 2099 CO_2 treatments, thus supporting previous studies which showed that water stress and the greenhouse gas interact differently as the levels of CO_2 increase (Serraj et al., 1999; Mera et al., 2006b).

Temperature was found to have relatively little impact on crop yields for the *OBS* and *AN* derived climates, where other aspects of the environment (i.e. precipitation) had a much higher influence on plant growth. When we used original *A2* model data to drive the crop models, we found that temperature became the variable with the highest contribution since the over-predicted precipitation reduced water stress to negligible amounts. Temperatures, however, had a clearly marked upward trend. The relationship between temperature and crop yields was significant with an R^2 of -0.43 for default CO_2 conditions and -0.44 for projected concentrations. It is a markedly negative relationship showing the detrimental effects that considerable rises in temperatures might have. This relationship may also help explain the decreasing yields towards the latter part of the simulated period in *A2*. Our results show that CO_2 enrichment may not have enough of a positive effect on the plant's response to higher temperatures when the temperatures are so extreme. Changing planting dates or using different cultivars may help circumvent this problem to some extent by placing crops in more favorable conditions to better take advantage of higher CO_2 levels, thus helping the crops to cope with potentially negative conditions in a future climate (Ziska, 1998; Ferris et al., 1999;

Mera et al, 2006b). We should also note that the planting dates we used are based purely on current plating methods for the sake of creating the observed simulations and thus may not be suitable for future crop management.

The use of a fine scale regional climate model has been found to be important for the prediction of potential future environmental effects on simulated soybean crops. CROPGRO has responded positively to the use of model anomalies, which reduced anomalously high rainfall and rainy days predicted by the RCM. More representative patterns in crop yields has been restored using this method with reduction of precipitation amounts and timing (i.e. amount of rainy days in a month). We found that rising temperatures near the end of the *A2* period could pose a significant threat to crops, as was found when CROPGRO was driven by original RCM data. The results from these two climate approximations (*AN*, *A2*) point to other methods, such as changing cultivar types and/or planting dates could help to take advantage of higher levels of CO_2 to enable soybean crops to better deal with the two most common environmental stresses faced by agriculture: high temperatures and low soil moisture contents. A different method for calculating anomalies should be tested to keep the temperature pattern in *A2* while retaining natural precipitation variability to help create more precise results.

We have seen how climate models can drive crop models successfully by changing environmental conditions. Environmental forcing has significant effects on biosphere-atmosphere interactions in the presence of climate change. Since feedbacks from agricultural systems could play an important role in modifying the climate, we suggest that future research should consider analysis of evapotranspiration and photosynthesis results from crop model simulations for their interaction with the atmosphere in future projections. This has potential impacts on improving dynamical land surface models and further testing of crop model response.

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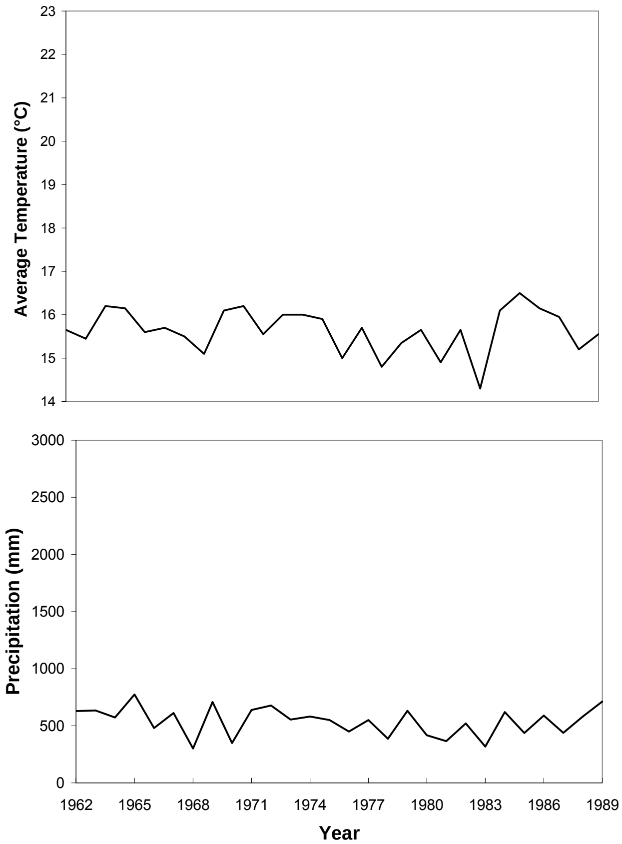

Figure 1. Observed climate data for the years 1962-1989. Average annual temperature (°C) on top, and total growing season precipitation (mm) on the bottom.

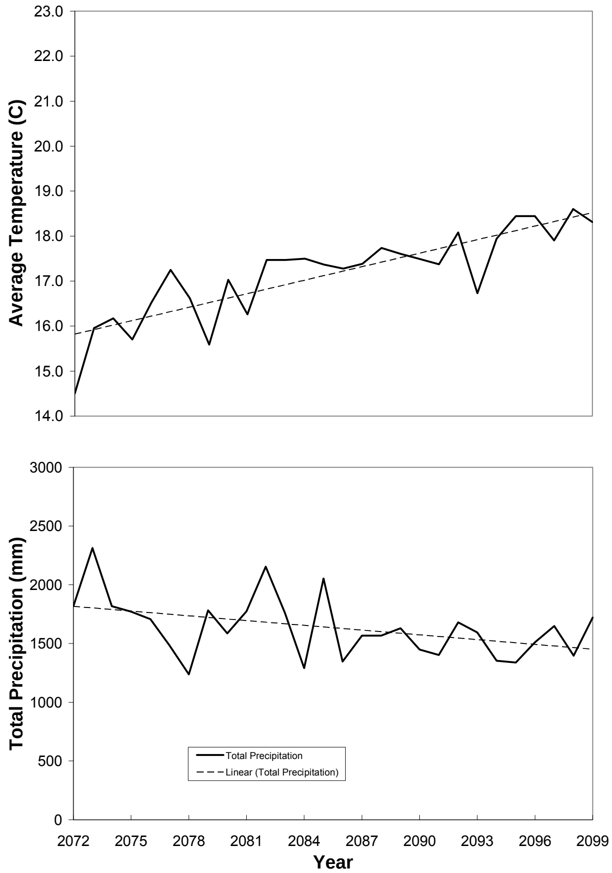

Figure 2. Original RCM climate data for the years 2072-2099. Average annual temperature (°C) on top, and total growing season precipitation (mm) on the bottom. There is a tendency to a warmer and relatively drier climate as shown by the trendlines.

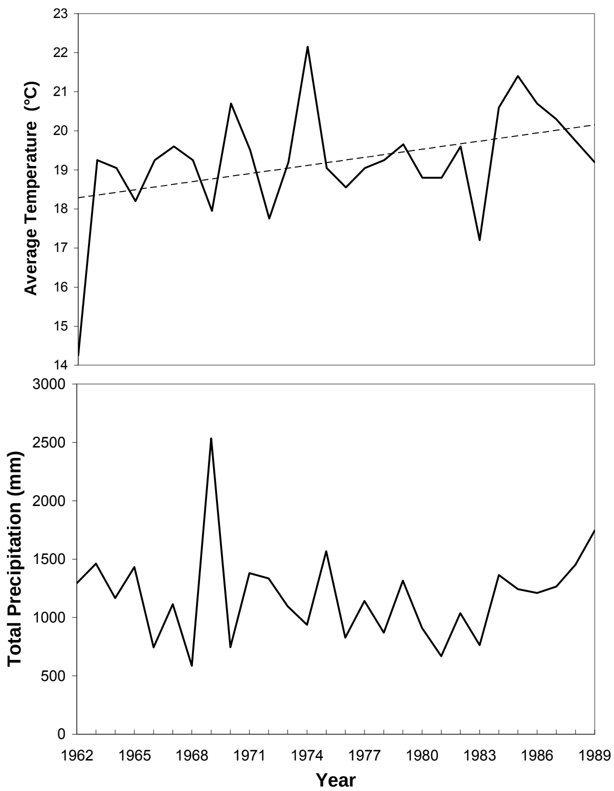

Figure 3. Model anomalies. Average annual temperature (°C) on top, and total growing season precipitation (mm) on the bottom. There is a slight trend towards warmer temperatures

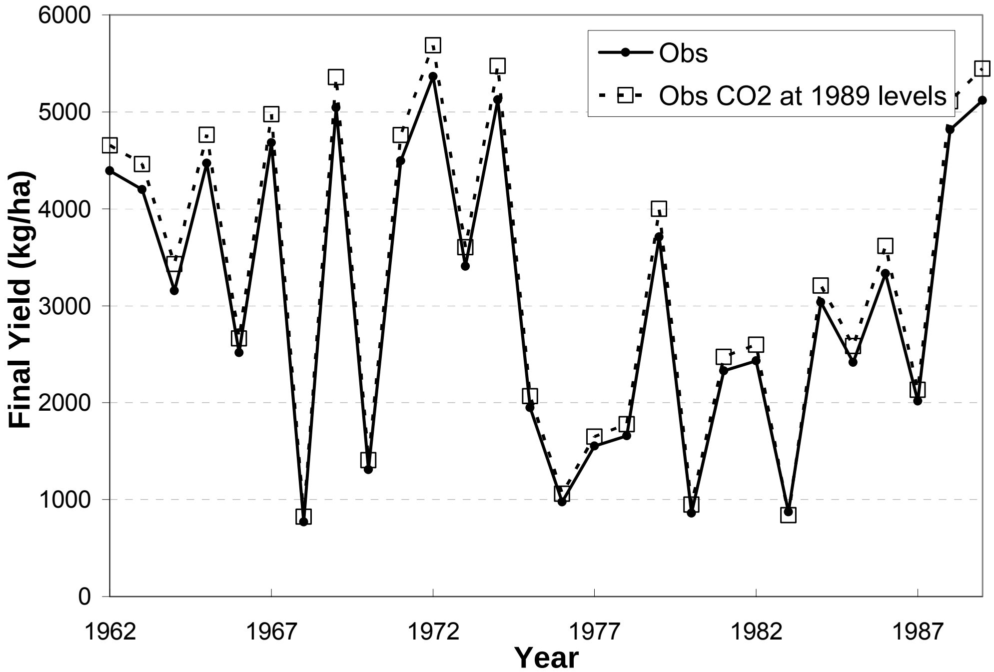

Figure 4a. Soybean crop yields for observed climate at default CO_2 level (solid) and 1989 CO_2 level (all in dashed).

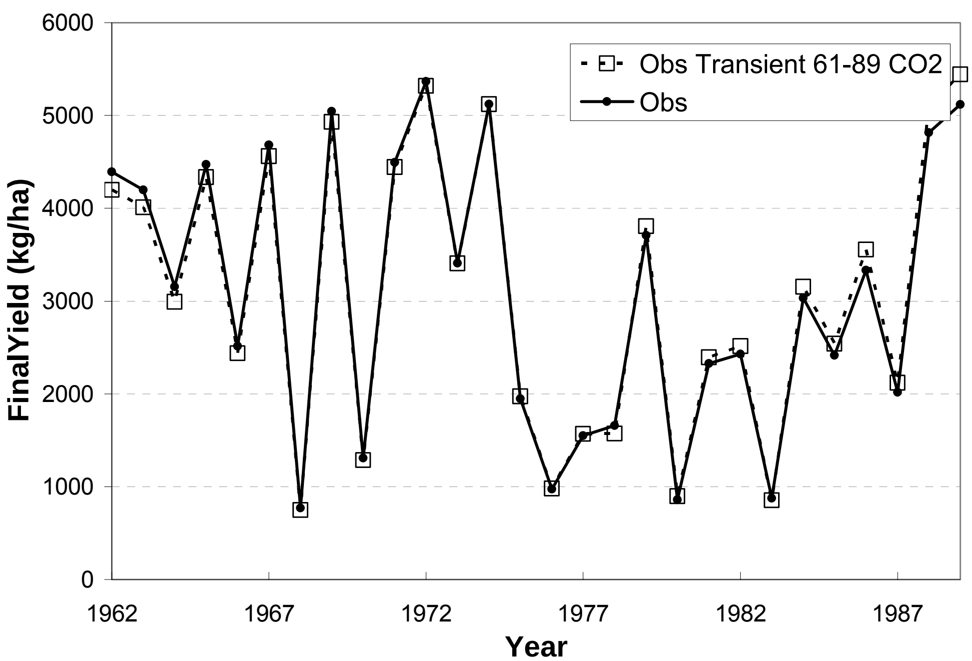

Figure 4b. Same as 4a but for transient *OBS* CO_2 levels, c) 2099 CO_2 levels, and d) transient *A2* CO_2 levels (all in dashed).

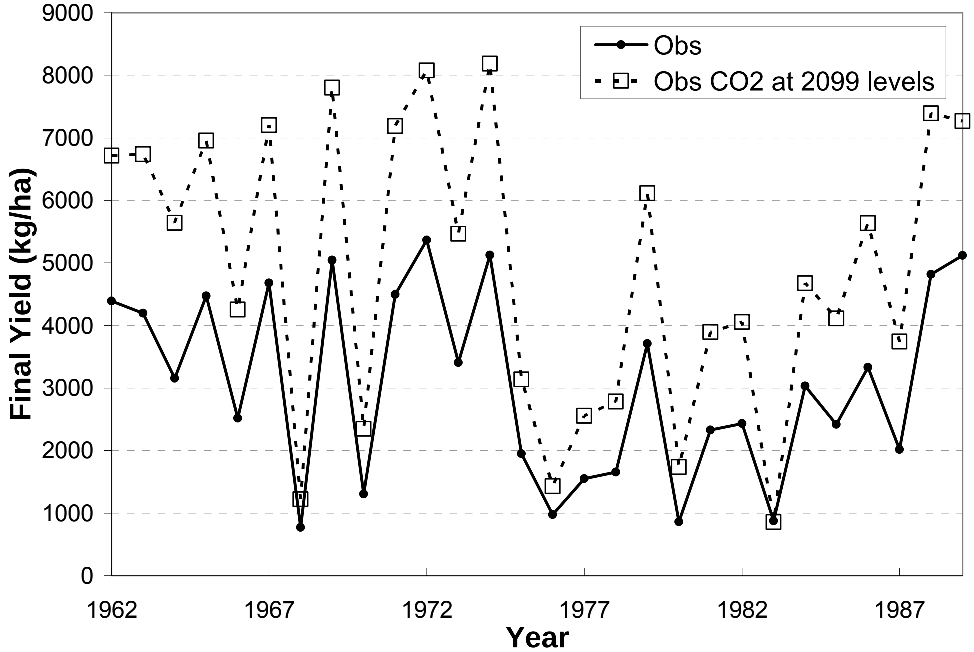

Figure 4c. Same as 4a but for 2099 CO_2 levels.

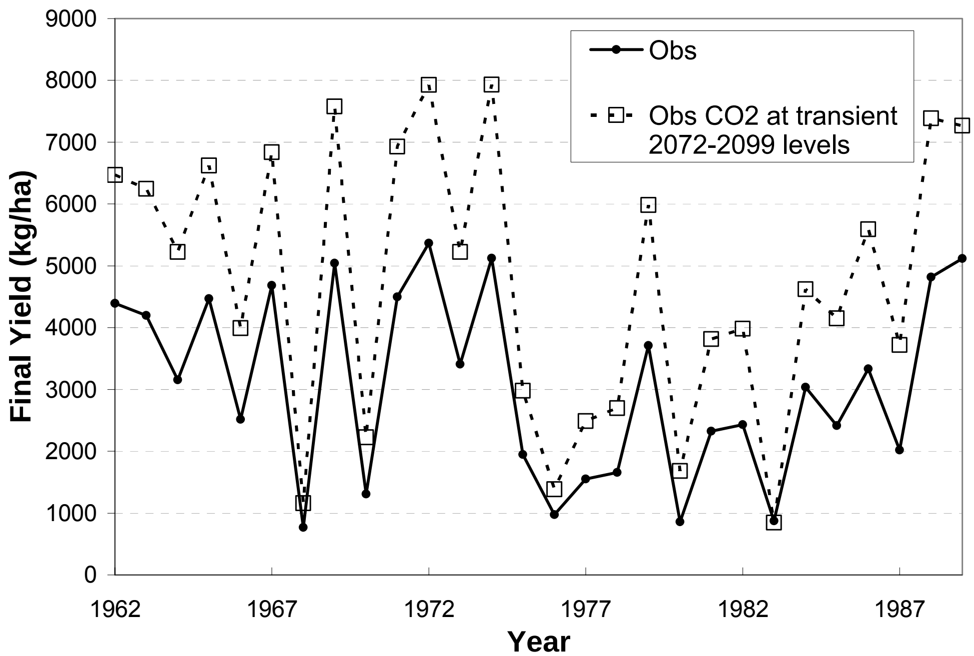

Figure 4d. Same as 4a but for transient *A2* CO_2 levels.

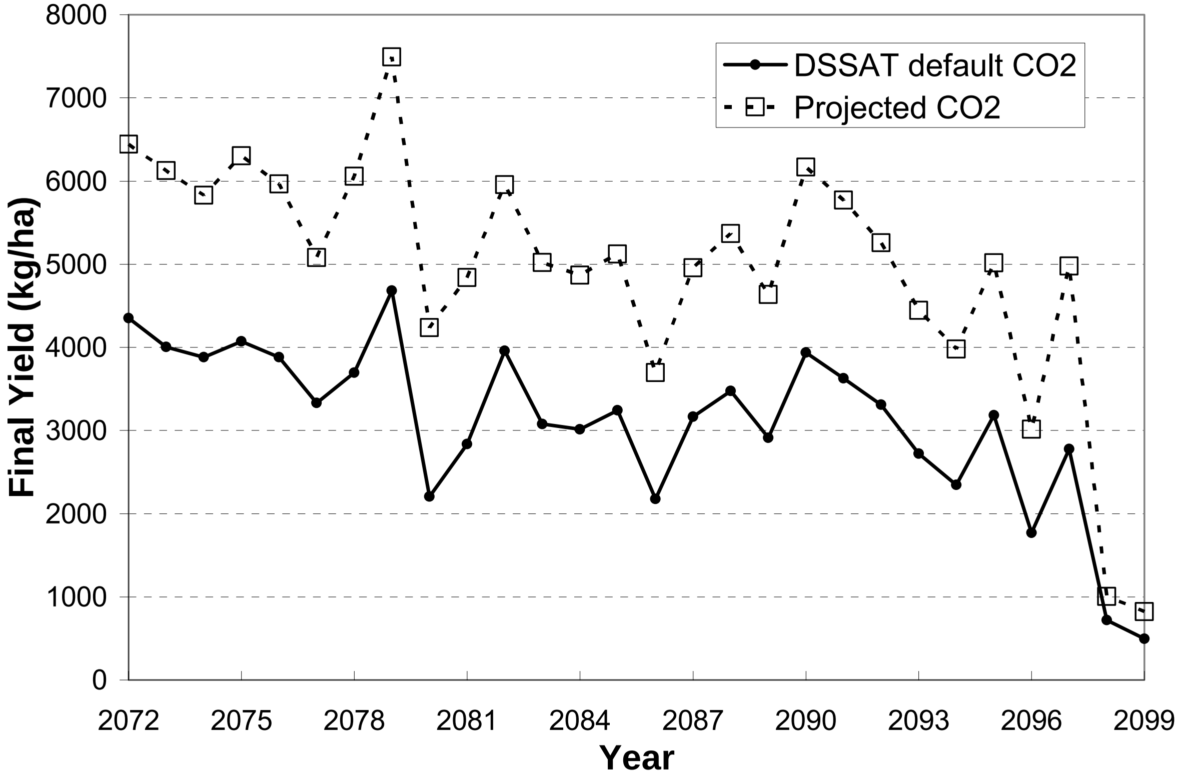

Figure 5. Annual soybean crop yields for *A2* scenario model predictions at default CROPGRO CO_2 level and projected 2099 level.

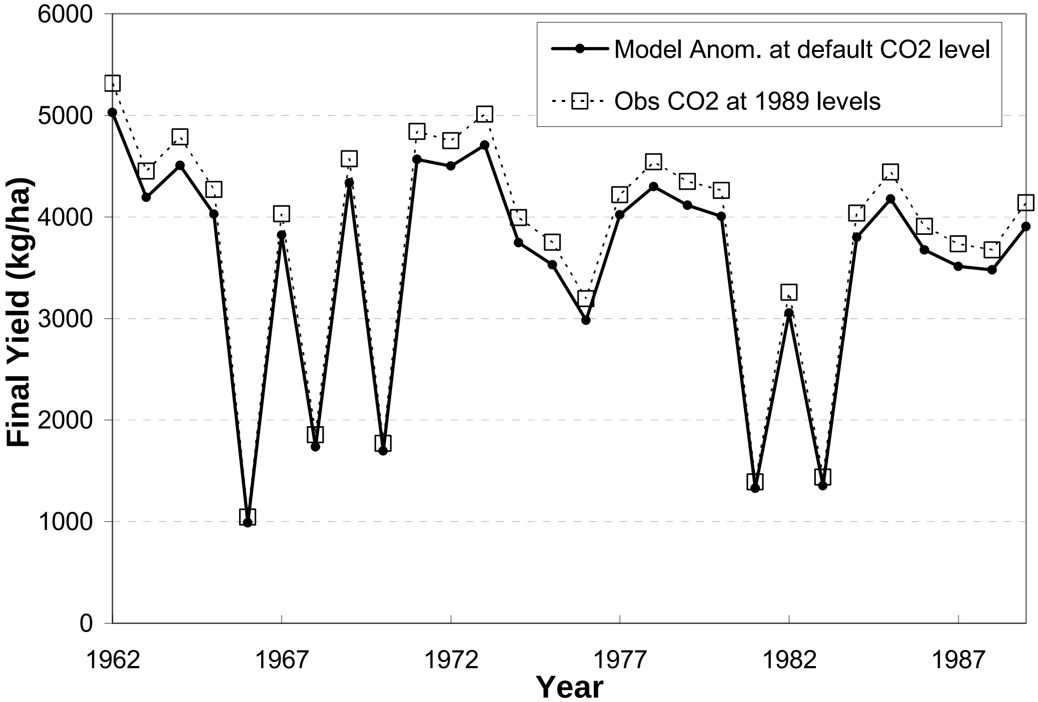

Figure 6a. Soybean crop yields for model anomalies at default CO_2 level (solid) and 1989 CO_2 level (dashed).

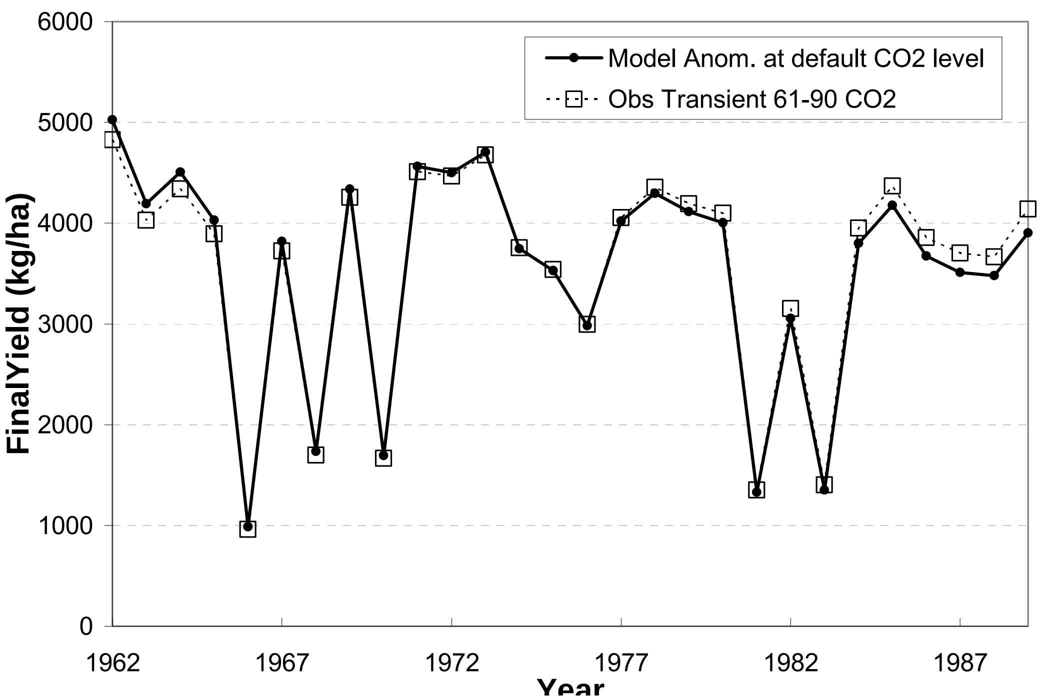

Figure 6b. Same as 6a but for transient *OBS* CO_2 levels.

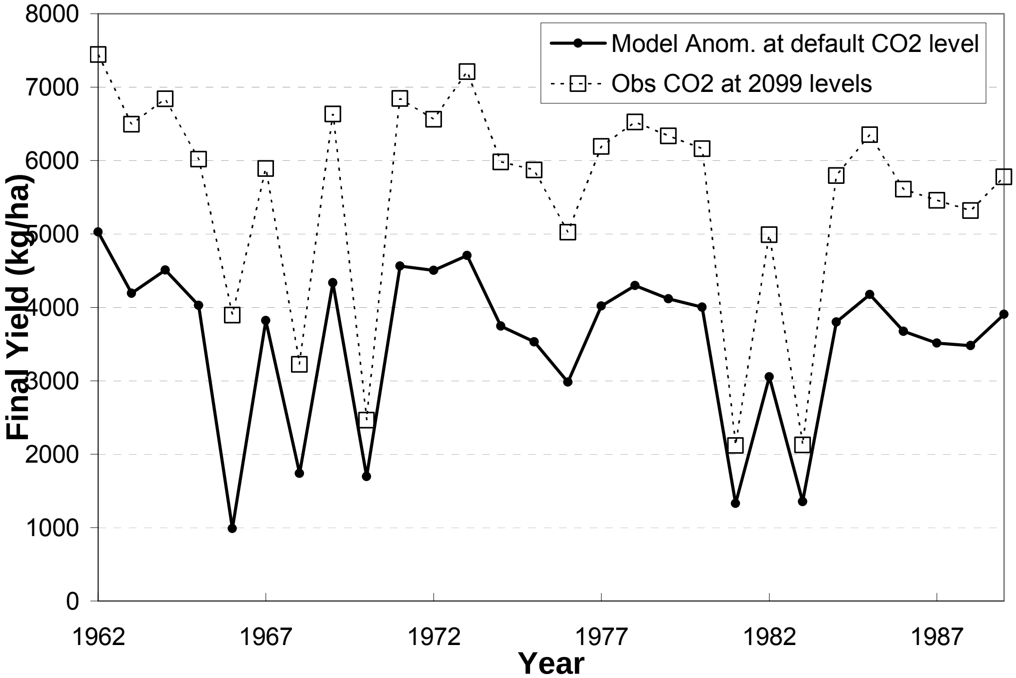

Figure 6c. Same as 6a but for 2099 CO_2 levels.

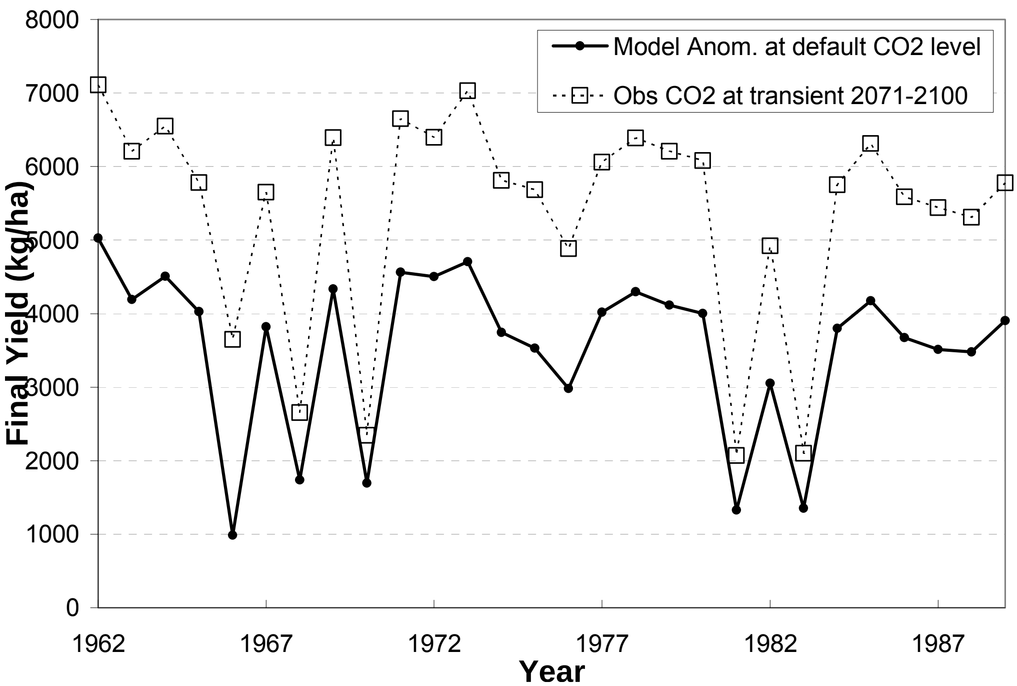

Figure 6d. Same as 6a but for transient *A2* CO_2 levels.

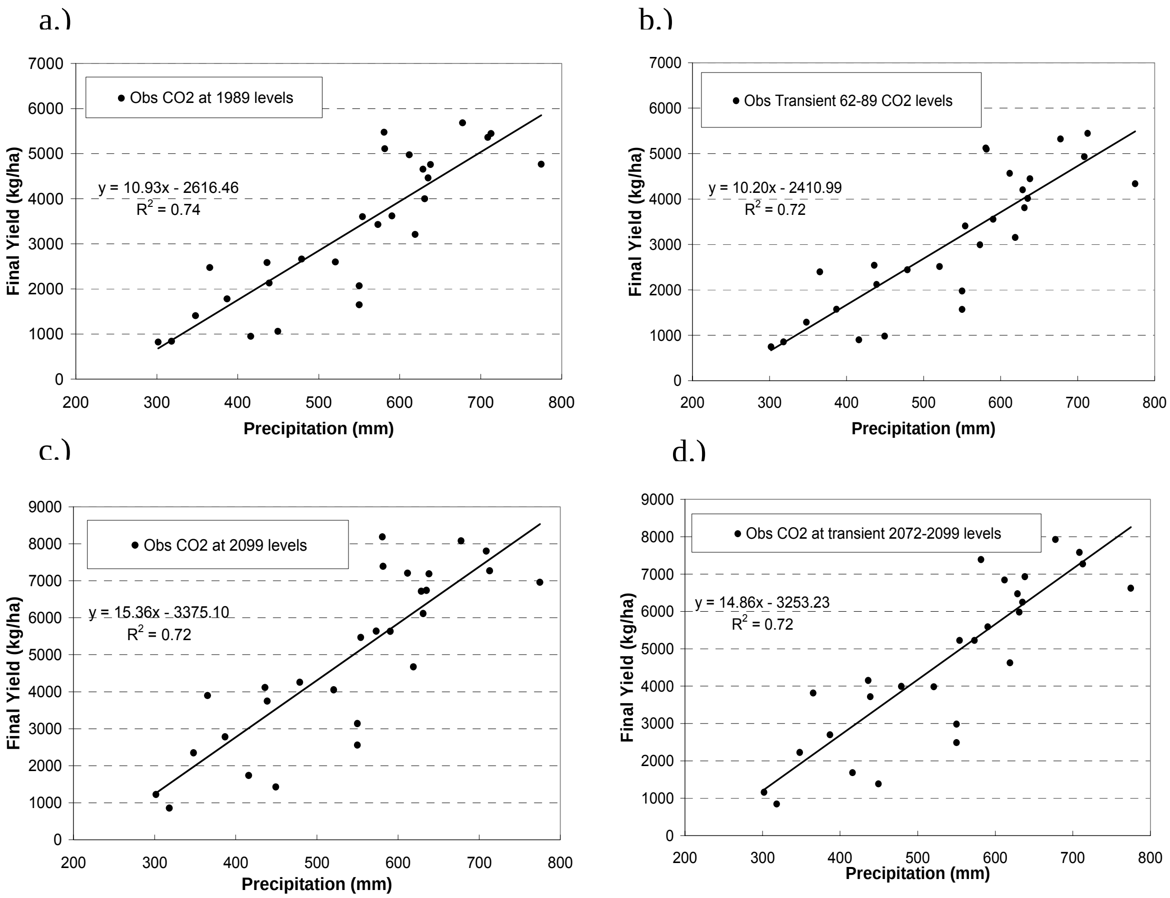

Figure 7. Relationships between soybean crop yields and total seasonal precipitation (mm) for observed climate at a) 1989 CO_2 level, b) transient *OBS* CO_2 levels, c) 2099 CO_2 levels, and d) transient *A2* CO_2 levels (all in dashed).

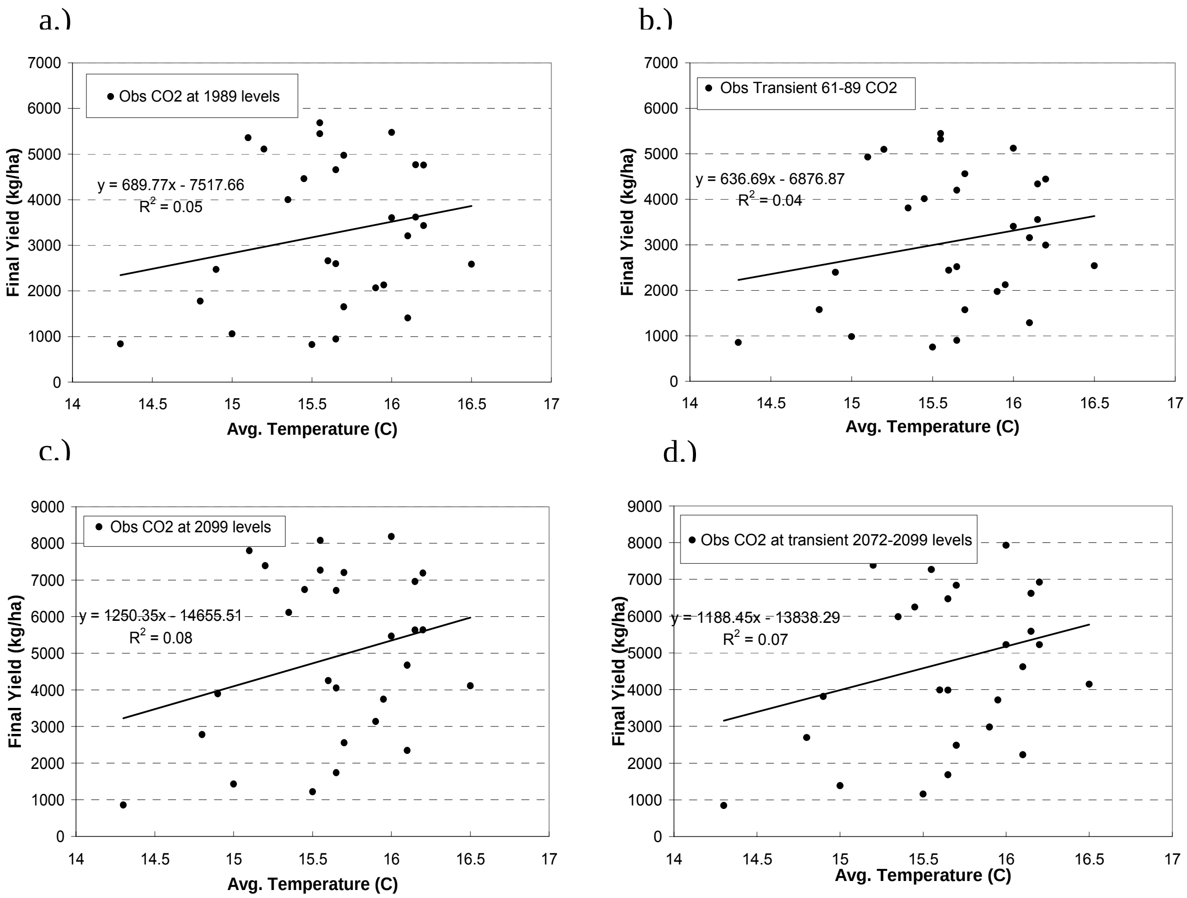

Figure 8. Same as figure 7, but for average yearly temperatures (°C).

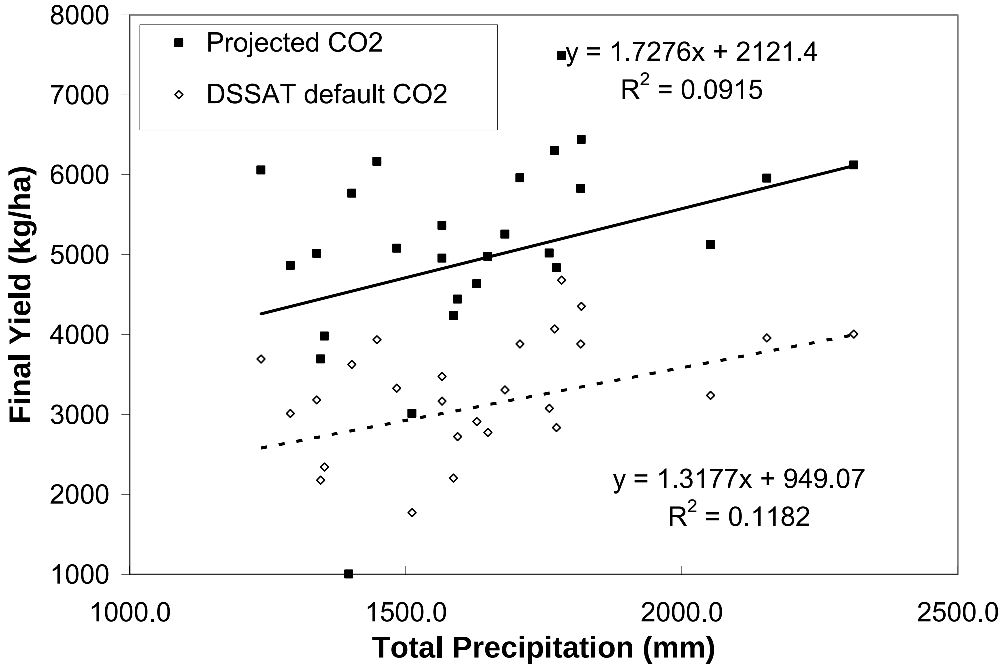

Figure 9a. . Relationships between soybean crop yields (kg/ha) and total yearly precipitation (mm) for future A2 climate at projected 2099 CO_2 level (empty circles) and CROPGRO default level (solid squares). Linear relationships shown for projected CO_2 (dotted) and default (solid).

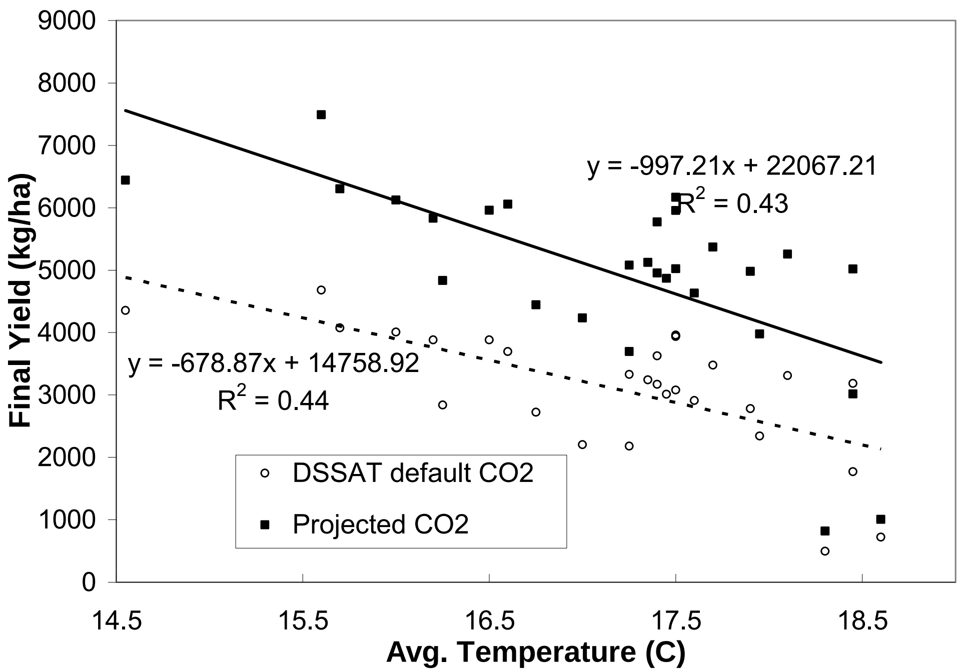

Figure 9b. . Same as 11a but for average yearly temperatures (°C).

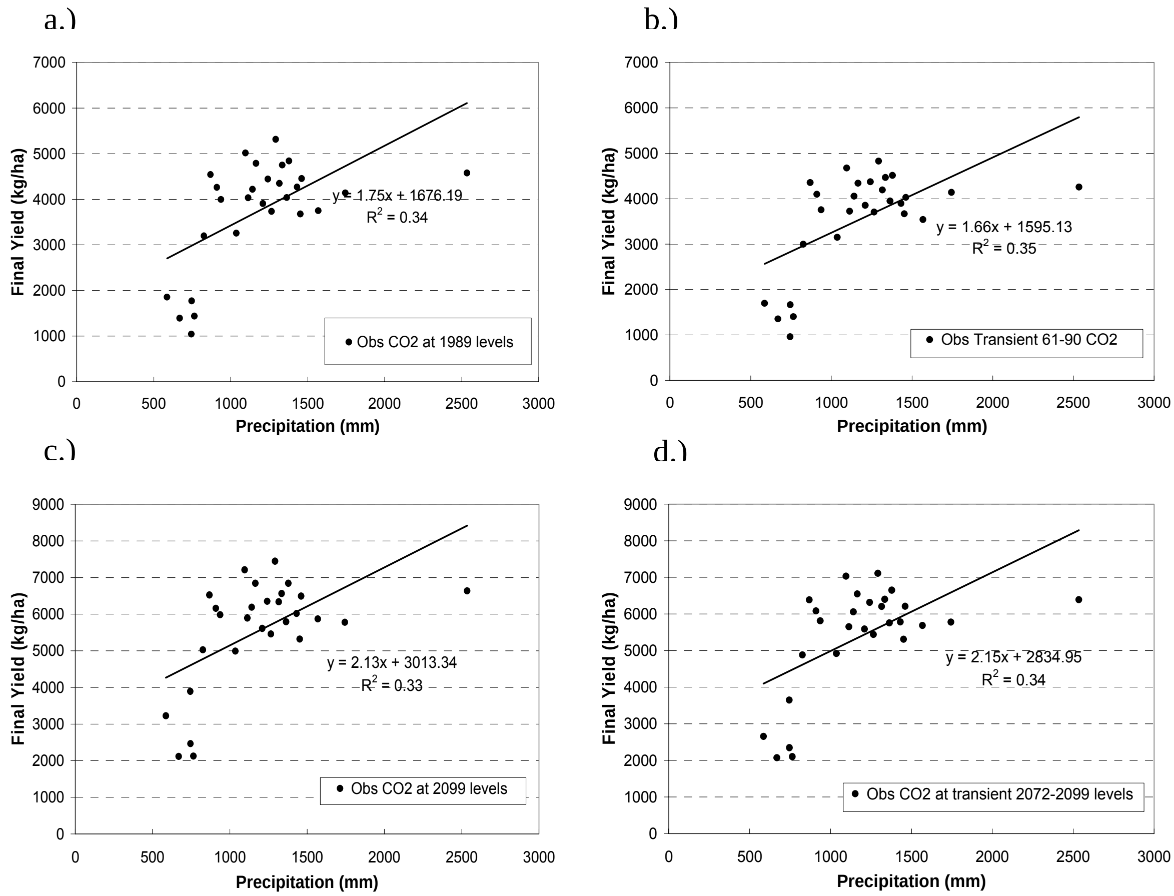

Figure 10. Relationships between soybean crop yields (kg/ha) and total growing season precipitation (mm) for *AN* model anomalies at a) 1989 CO_2 level, b) transient *OB* CO_2 levels, c) 2099 CO_2 levels, and d) transient *A2* CO_2 levels.

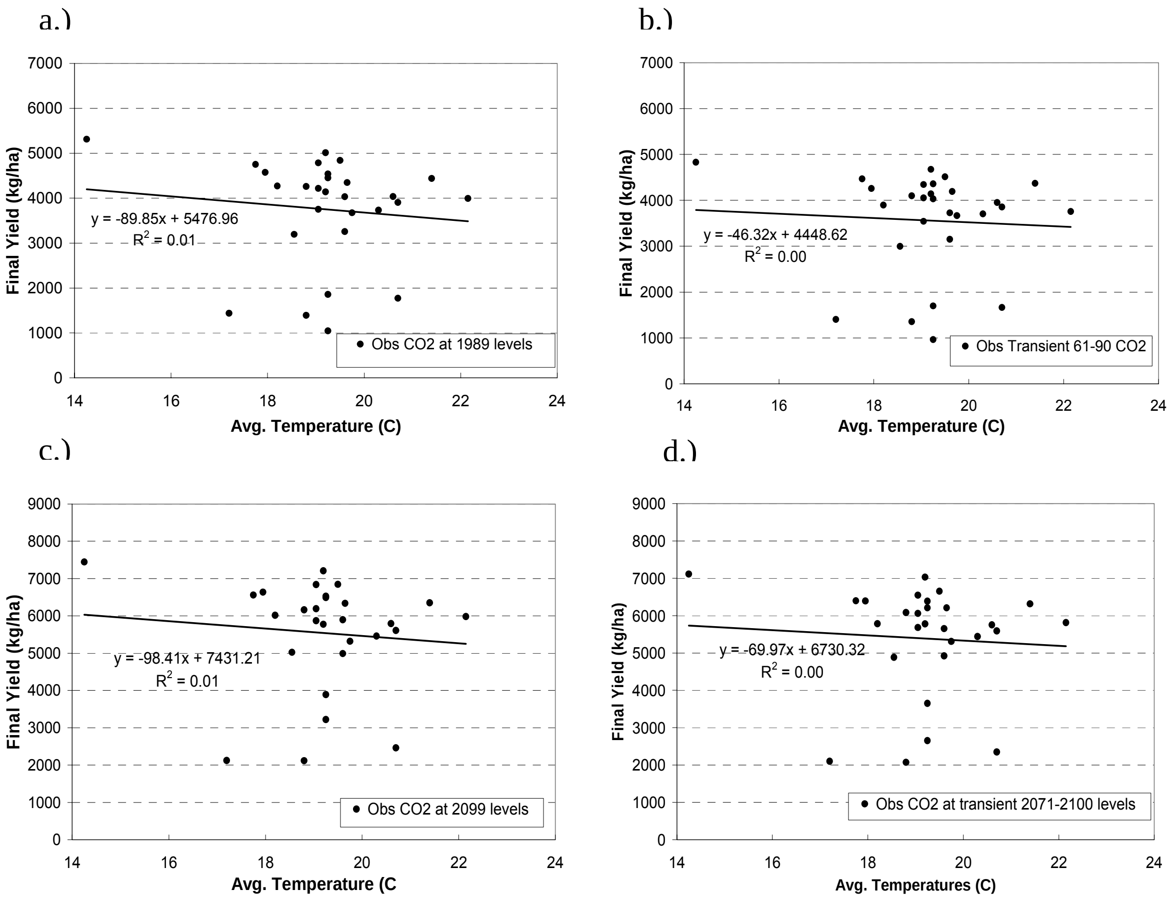

Figure 12. Same as figure 12 but for average yearly temperature (°C).

4. Potential Individual versus Simultaneous Climate Change Effects on Soybean (C_3) and Maize (C_4) Crops: An Agrotechnology Model Based Study

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Abstract

Landuse/landcover change (LULCC) induced effects on regional weather and climate patterns and the associated plant response or agricultural productivity are coupled processes. Some of the basic responses to climate change can be detected via changes in radiation (R), precipitation (P), and temperature (T). Past studies indicate that each of these three variables can affect LULCC response and the agricultural productivity. This study seeks to address the following question: W*hat is the effect of individual versus simultaneous changes in R, P, and T on plant response such as crop yields in a C_3 and a C_4 plant*? This question is addressed by conducting model experiments for soybean (C_3) and maize (C_4) crops using the DSSAT: Decision Support System for Agrotechnology Transfer, CROPGRO (soybean), and CERES-Maize (maize) models. These models were configured over an agricultural experiment station in Clayton, NC [35.65°N, 78.5°W]. Observed weather and field conditions corresponding to 1998 were used as the control. In the first set of experiments, the CROPGRO (soybean) and CERES-Maize (maize) responses to individual changes in R and P (25%, 50%, 75%, 150%) and T (±1, ±2°C) with respect to control were studied. In the second set, R, P, and T were

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simultaneously changed by 50%, 150%, and ±2°C, and the interactions and direct effects of individual versus simultaneous variable changes were analyzed. For the model setting and the prescribed environmental changes, results from the first set of experiments indicate: (i) Precipitation changes were most sensitive and directly affected yield and water loss due to evapotranspiration; (ii) radiation changes had a non-linear effect and were not as prominent as precipitation changes; (iii) temperature had a limited impact and the response was non-linear; (iv) soybeans and maize responded differently for R, P, and T, with maize being more sensitive. The results from the second set of experiments indicate that simultaneous change analyses do not necessarily agree with those from individual changes, particularly for temperature changes. Our analysis indicates that for the changing climate, precipitation (hydrological), temperature, and radiative feedbacks show a nonlinear effect on yield. Study results also indicate that for studying the feedback between the land surface and the atmospheric changes, (i) there is a need for performing simultaneous parameter changes in the response assessment of cropping patterns and crop yield based on ensembles of projected climate change, and (ii) C_3 crops are generally considered more sensitive than C_4; however, the temperature-radiation related changes shown in this study also effected significant changes in C_4 crops. Future studies assessing LULCC impacts, including those from agricultural cropping patterns and other LULCC – climate couplings, should advance beyond the sensitivity mode and consider multivariable, ensemble approaches to identify the vulnerability and feedbacks in estimating climate-related impacts.

KEY WORDS: Land Surface Response, Climate Change Impacts, Crop Yield, Soybean, Maize, Crop Models, Evapotranspiration

4.1 Introduction

Alterations in agricultural activity continue to be a major driver of regional landuse/landcover change (LULCC). Feedbacks that occur due to LULCC are noticed in shifts in regional climate patterns, which in turn lead to changes in the vegetation productivity and land surface feedback (Pielke et al., 2002). As discussed in Foley et al. (2005), an increase in the human population and the demand for food and fiber has expanded the croplands, pasturelands, plantations, and urban areas in recent decades.
Croplands and pastures presently occupy nearly 40% of the land surface and have become one of the largest landuse categories, rivaling forest cover in extent. The last four decades have also seen a doubling of the world harvest, some of which is due to about a 12% increase in world cropland area, but most is due to cultivar and other environmental, technological, and management factors (Foley et al., 2005). Thus, changes in the cropping patterns in response to crop cycle, mixed agriculture, environmental and climate change considerations, and agricultural demand continue to be important factors.

Studies of climate change impacts on agriculture initially focused on rising CO_2 levels (Curry et al., 1990; Brown et al., 1997). A wide range of literature exists in synthesizing both the negative and the positive effects of CO_2 increase in plants (Curtis and Wang 1998). Studies such as Hansen et al. (2002) and Pielke et al. (2005) suggest, following their discussion, that additional aspects of climate change (e.g. radiation, temperature, precipitation) need to be studied to assess the impact of climate change, beyond the CO2 increase, on regional productivity.

Studies such as Mearns et al. (1996, 2003), Rosenzweig and Tubiello (1997), Iglesias et al. (1996), and Izaurrable et al. (2003) indicate that precipitation is a leading factor affecting crop yields. In a study by Ferris et al. (1999), water deficit treatments reduced the overall biomass of soybeans, regardless of CO_2 enrichment. It has become increasingly evident that complex interactions of precipitation occurrence can impact the overall health of crops as well as regional productivity. Consequently LCLUC prediction models use precipitation change as one of the criteria in developing the trajectory of the landuse change.

Similarly, studies that have monitored the influence of changes in radiative forcing on crops have focused on the impact of the increase in ultra-violet radiation (Booker et al. 1992; Fiscus et al. 1994; Miller et al. 1994). Limited attempts have also been made to observe the combined effects of changes in UV-B radiation, temperature, and CO_2 (e.g. Mark and Tevini 1997). Recent studies (Chamedies et al. 1999; Niyogi et al. 2004) analyzed changes in these radiative properties (diffuse radiation) and suggested that radiative dimming may aid crop productivity. The increase in aerosols and clouds created
by volcanic eruptions as well as biomass burning are also being recognized as factors that can affect biospheric productivity and structure (Hansen et al. 1999; Gu et al. 2003).The natural and anthropogenic aerosols absorb solar radiation, and this solar absorption within the atmosphere, together with the reflection of solar radiation to space, leads to a reduction in the solar radiation absorbed by the Earth's surface. This would tend to have a redistribution effect on surface heating and change agricultural productivity in certain areas (Pielke et al. 2005).

In addition, temperature changes can affect crop productivity (Fiscus et al. 1997). Higher temperatures may increase plant carboxilation and stimulate higher photosynthesis, respiration, and transpiration rates. Meanwhile, flowering may also be partially triggered by higher temperatures, while low temperatures may reduce energy use and increased sugar storage. Reddy et al. (2002) concluded that the rates of plant growth and development would continue to increase in the southern U.S. because of enhanced metabolic rates at higher temperatures, combined with increased carbon availability. Combined changes in radiation and temperatures can produce various effects. For example, an increase in aerosols can typically reduce surface radiation levels, and hence, surface temperatures. If these aerosols are carbon-dominated, they can cause warming, while sulfate aerosols can cause further cooling (Pielke et al. 2005; Niyogi et al. 2005).

Changes in temperature can also affect air vapor pressure deficits, thus impacting the water use in agricultural landscapes (Kirschbaum 2004). This coupling affects transpiration and can cause significant shifts in temperature and water loss. These feedbacks contribute to regional changes in precipitation and cloudiness, leading to changes in radiation (Pielke et al. 2001).

Therefore, for climate change studies on regional productivity, important additional environmental or regional climate changes beyond CO_2 increase such as radiative feedback, temperature, and precipitation are still in need of careful study. Another significant conclusion from past studies is the potential for interactive effects of multiple environmental factors on the response of plants. For example, Kirschbaum (1994), Idso and Idso (1994), Ham et al. (1995), Drake et al. (1997), Eastman et al. (2001), and Carbone et al. (2003) show that assessment of the role of multiple effects and isolation of individual impacts are significant in the effects of climate change on plant response. The response of C_3 and C_4 crops to elevated CO_2 levels when exposed frequently to water stress or changes in climatic factors such as temperature or rainfall may provide inconsistent results because of the feedback between hydrology and nutrient relations (Rosenberg 1992; Idso and Idso, 1994; Ham et al., 1995; Samarakoon and Gifford, 1996; Drake et al., 1997; Deepak and Agrawal, 2001). Building on these considerations, our objective in this study is to assess and analyze the individual and multiple interactions of radiation, temperature, and precipitation changes on the regional productivity of C3 and C4 crops. For this, we use two well-established crop modeling systems (CROPGRO and CERES-Maize as part of the Decision Support System for Agrotechnology Transfer: DSSAT, version 3.5) to study the effects of environmental/climate changes in radiation, temperature, and precipitation on crops, specifically soybeans and maize, through crop yield and canopy water loss/evapotranspiration.

The paper is organized as follows. Section 2 discusses the methodology of the study and includes a description of the crop models used as well as the model calibrations and synthetic experiments conducted. Section 3 presents the results and discussion - first for soybean and maize sensitivity to each variable change, and then for the combined analysis of the multiple effects. The conclusions are presented in Section 4.

4.2 Methodology

Soybeans and maize were chosen as representative crops because they are important food crops grown throughout the world. These two crops also belong to two different types of photosynthesis pathways (C3 for soybeans and C4 for maize), which often dictate the cycling and photosynthetic processes of water and nutrients. In the following sections, we describe the models used in the design of the experiments and the analysis method employed in the study. A brief overview of the calibration dataset is also provided.

4.2.1 Models

A number of studies that use DSSAT to predict effects on crops due to climate change have yielded varying outcomes. The majority of these studies have used models to learn about the effect of doubling CO_2 levels. For example, Wolf (2002a) considered a scenario with increased amounts of CO_2 and showed that yields increased in proportion to other variable changes such as solar radiation and temperature. Effects of change in precipitation have also been studied (Hansen et al., 1996; Wang et al., 2001; Magrín et al., 2002), and other studies have been concerned with the effects of temperature and solar radiation changes (Wolf and van Diepen, 1995; Maytín et al., 1995; Brown and Rosenberg, 1997; Southworth et al., 2000; Wolf, 2002b). Generally, significant changes in yield resulted when the precipitation factor was altered.

a. Calculation of Yield in CROPGRO and CERES-Maize

We use the CROPGRO model as part of the Decision Support System for Agrotechnology Transfer (DSSAT) to measure soybean response. CROPGRO is a predictive, deterministic model which simulates physical, chemical, and biological processes in the plant and its associated environment. The model simulates crop yields and related agronomic parameters and is constructed to predict primary plant processes as a function of weather, soil, and crop management conditions. The models are processoriented and consider crop development, crop carbon balance, crop and soil N balances, and soil water balance (Boote et al., 1998). Crop development in the model is differentially sensitive to temperature, photoperiod, water deficit, and nutrient stresses during various growth phases and is expressed as the physiological days per calendar day (PD d-1).

The CROPGRO model has typically been used to study the variability of precipitation on soybean yield in various regions of the world. Site-specific evaluations of the CROPGRO system have been performed over different locations such as Missouri (Wang et al., 2001), Hawaii (Ogoshi et al., 1998), and other US sites including North Carolina (Boote et al., 1997), which is used in this study. A multi-year, multi-state compilation of studies by Jones et al. (2004) concluded that the CROPGRO model could be used to simulate a variety of environmental conditions, including the drought response of soybean cultivars in various drought stress environments. An in-depth study by Boote et al., (2001) used a variety of growth analysis datasets to test the effects of temperature and water deficits on the C balance and N balance processes of the CROPGRO-Soybean model. The study also surveyed the existing literature to identify data from controlled-environment studies suitable and/or significant to the testing of soybean response to temperature and CO_2.

The CERES-Maize (Crop Environment Resource Synthesis-Maize; Jones and Kiniry, 1986) model is also a part of the DSSAT and is a predictive, deterministic model. The model is designed to simulate corn growth, soil, water, temperature, and soil nitrogen dynamics on a field scale for one growing season, and belongs to the same DSSAT family as CROPGRO. CERES-Maize derives daily rates of crop growth (PGR, g plant^{-1} d^{-1}) as the product of light intercepted by the canopy (IPAR, MJ plant^{-1} d^{-1}) and radiation use efficiency (RUE, g MJ^{-1}). When the crop is under environmental stress, this approach has limits in calculating photosynthesis and respiration (Lizaso et al. 2005).Specifically, the photosynthetic rate in maize increases with temperature, to a maximum around 35°C, then decreases at higher temperatures (Oberhuber and Edwards, 1993; Naidu et al., 2003). Recently, the model was updated by comparing the output against the field plots in order to more adequately represent the crop under stress conditions (Lizaso et al. 2005).

The rate of development in CERES-Maize is controlled by temperature (growing degree days: GDD). The number of GDD that accumulate on a given calendar day are based on daily maximum and minimum temperatures, and are a triangular function of trapezoidal function that is defined by a base temperature, a couple of optimum temperatures, and a maximum temperature (Jones et al., 2003). Day length sensitivity is a cultivar-specific input that can influence the total number of leaves formed by modifying the length of certain growth phases. Leaf area expansion is controlled by GDD and nitrogen
and water stresses. Daily plant growth is calculated by converting intercepted PAR into plant dry matter with a crop-specific radiation-use efficiency parameter (Jones et al., 2003).

Similar to CROPGRO, the CERES-Maize model has been tested in several areas of the world to study maize sensitivity to climate change. For example, Shultze et al. (1996) used CERES-Maize to evaluate the impact of climate change in Africa. After employing different climate scenarios for the 21st century, they found that the CO_2 enrichment effect counteracted the relatively modest changes in temperature and precipitation. Similarly, Iglesias (1994) demonstrated climate change scenarios in a greenhouse-induced warmer climate, based on GISS, GFDL, and UKMO climate models, and they projected an increase in evaporative rates and a more vigorous water cycle.

Other studies concerning the effect of climate change and variability showed that the maize yields from CERES-Maize are sensitive to increased temperature and decreased precipitation (e.g. Maytín et al. (1995) for Venezuela, Jinghua and Erda (1996) for China, and Brown and Rosenberg (1997) for central U.S.). A negative correlation between maize yields and radiation over Europe was also reported by Wolf and van Diepen (1995).

These results are important to present and future studies of maize and soybean crops as they lay the groundwork for assessing the regional effects of climate change and agricultural productivity (Rosenberg 1992; Easterling et al. 2001; Mearns et al. 2003).

b. Calculation of ET in CROPGRO and CERES-Maize

The default method for both CROPGRO and CERES-Maize is the Priestley and Taylor (1972) method. All DSSAT models use this method to calculate potential evapotranspiration (PE). Due to this, the values of calculated ET for both models will be similar. The Priestley-Taylor method calculates PE through the following equation:

$$c_t L_v \rho_w PE_s = \frac{1.26 \Delta R_n}{\Delta + \gamma} \tag{1}$$

where, PE_s = surface dependent potential evaporation (mm d^{-1}), c_t = conversion constant = 0.01157 W md MJ^{-1} mm^{-1}, L_v = latent heat of vaporization = 2448.0 MJ Mg^{-1}, R_n = net radiation (W m^{-2}), γ = psychrometer constant = 0.067 kPa K^{-1}, ρ_w = density of water = 1 Mg

$m^{3,}$ Δ = slope of the vapor pressure/temperature curve (kPa K_{-1}). The PE is dependent only on net radiation and daily air temperature.

4.2 Experimental

We provided 25 different climate scenarios/weather regimes to CROPGRO and CERES-Maize for different radiation, temperature, and precipitation conditions. The aim was to assess their effect on the growth, yield, and water use of soybeans and maize.

To create the different meteorological regimes, the weather module used in the DSSAT system was altered. Both CROPGRO and CERES-Maize call the weather module to input, generate, and calculate the daily and hourly weather values. The model includes a "weather modification" feature that can alter historical or generated daily weather values by user-specified multipliers or increments (Porter et al., 2000).

We used observed meteorological and environmental (such as soil, plant species, and management practice) data for 1998 from Clayton, North Carolina [35.65°N, 78.5°W]. This particular location and period was used for the control values because of our familiarity with the region (thus potentially reducing the uncertainty), and also because the period was considered "normal" (i.e. without any significant environmental stress). Further, the field observations were important for testing the model results and developing scenarios that would be based on realistic configurations. At the field site, the annual total precipitation was 1201.4 mm, the daily average solar radiation was 13.7 MJ m^{-2} day^{-1},

and the average air temperature was 23.1°C. Figure 1 shows the variation in individual variables throughout the growing season. All other data required to execute DSSAT provided for the 1998 Clayton what followed the observations reported in Boote et al. (1997).

The “control” meteorological data were modified as follows: for precipitation (P) and solar radiation (R) changes, the control data were altered by 25%, 50%, 75%, and 150%, and for temperature (T) changes of ±1°C and ±2°C of the control. Eight additional runs were performed to analyze the effects of simultaneous interaction between the changes in all three variables for ±50% of control solar radiation and precipitation, and ±2°C of the control temperature. The ranges were based on the summary projections based on climate model results, perceptions of the regional agricultural and natural resource managers and the extension specialists community, and the analysis of past regional climate data for seasonal variations. Even then, these changes are not necessarily representative of what is the expected climate change; rather, they were generated for developing statistically significant sensitivity estimates. The runs were labeled as shown in Table 1.

The model output included crop age (date), biomass (kg ha^{-1}), and evapotranspiration (mm). For the simulation, the selected start date for the soybean growing season is May 15 and the typical harvest date is October 1; for corn, the season begins on April 15 and generally runs through August 22. Additional processing of the output data was necessary to compare the different runs, in particular, since dates such as the time of harvest, first flowering, and crop maturity varied by no more than one day for soybeans, but could vary up to two weeks for maize. Also, as seen in the figures, the highest number for the soybean crop yield (biomass kg ha^{-1}) occurred before harvest in what is called the “physical maturity” stage. This number, however, was not used for the final comparisons because in maize, the “harvest maturity” number has the highest yield.

To understand the effect of individual as well as simultaneous changes in radiation, temperature, and precipitation, a statistical/factorial design of an experiment based technique was employed (Stein and Alpert 1993). The most important direct effects and interactions were estimated as (P. Alpert, Personal Communication, 2005):

$$E_0 = mRmPmT \tag{2a}$$

$$E_R = pRmPmT – mRmPmT \tag{2b}$$

$$E_P = mRpPmT – mRmPmT \tag{2c}$$

$$E_T = mRmPpT - mRmPmT \tag{2d}$$

$$E_{RP} = pRpPmT - (pRmPmT + mRpPmT) + mRmPmT \tag{2e}$$

$$E_{RT} = pRmPpT - (pRmPmT + mRmPpT) + mRmPmT \tag{2f}$$

$$E_{PT} = mRpPpT - (mRpPmT + mRmPpT) + mRmPmT \tag{2g}$$

$$E_{RPT} = pRpPpT - (pRpPmT + pRmPpT + mRpPpT) + (pRmPmT + mRpPmT + mRmPpT) – mRmPmT) \tag{2h}$$

The terms on the right-hand side of the equation are the same as provided in Table 1. The terms on the left-hand side of the equation are as follows: E_0 = background effect or the model results, with the least of the R, P, T settings being used in estimating the interactions as additional magnitudes of the various effects are added; E_R, E_P and E_T = individual contributions or the direct effect of the variable; E_{RP}, E_{RT}, and E_{PT} = interactions between two variables; E_{RPT} = triple interactions due to incremental changes in R, P, and T. The Es in the equations represent the effect.

4.3. Results and Discussion

4.3.1 Effects of Changes in the Radiative Flux

Radiation directly contributes to plant photosynthesis and has a feedback effect on water use efficiency by modifying surface radiative energy balance. As seen in Figure 2a, radiation shows a nonlinear response where the final biomass is highest for values that are at 75% of the “control” and are generally similar when the radiation value increases or decreases by 50%. The lowest yields are obtained for the smallest radiation values (25% of control), while the second-lowest yields occur with the largest prescribed radiation levels (150% of control). The non-linear response of radiation is also noticed in the modeled growth rate. For example, the growth rate at 50% radiation is higher than the control values between days 15 and 85. For the 150% radiation values, the plot also shows a slight dip in the growth, ranging from around 500 kg ha^{-1} for 150% between days 91 and 102 before continuing to rise. This dip occurs at the “end leaf” phonological development stage. The increase in crop growth continues for all three sets of simulations until the “end pod” stage.

The effect of radiation changes on soybean evapotranspiration (ET) is shown in Figure 2b. Due to the relative wetness at the study site in 1998, the actual evapotranspiration should occur at nearly the potential rate (PET) and should correlate significantly with the radiation. Changes in ET also affect yield because the model simulates moisture stress through the ratio of ET/PET. If this ratio is < 1.0, it indicates that the crop has reduced stomatal conductance to prevent desiccation. The rate of photosynthesis varies proportionately with the ratio of ET/PET. This, in turn, simulates the impact that plant water stress has on crop growth. Similarly, a ratio of potential root water uptake and potential transpiration is used to reduce plant turgor and expansive crop growth. Generally, as soil water becomes more limiting (ET/PET < 1.5), the turgor pressure in leaves would decrease and affect leaf expansion before photosynthesis is reduced. We thus find that ET generally correlates with incoming radiation values, and that the ET values show higher variation with increased radiation levels. That is, significantly more variation occurs between ET values for

75% versus 25% of the control as compared to 150% and the control simulation itself. This response is expected as ET or latent heat flux is a fraction of the global insolation.

The nonlinear impact of changes in the radiation level is also seen in the model-simulated plant nitrogen (N) levels (Figure 2c). Since N concentration also depends on plant size, the highest concentrations are at the beginning of the simulation, with a trough during the middle of the season, and an increase in nitrogen levels by harvest time. The only significant differences occurred on day 15 and after day 100. Here, 25% radiation had the largest value, and the values less than the control remained close to each other. Overall, N concentrations over the plant growth period do not appear to depend on the radiation levels. The end concentrations, however, may be a weak function of global radiation, which could also be due to a feedback of other factors affecting soil and plant biophysical processes.

For the maize crop, biomass yields exhibited patterns similar to those of soybeans in response to changes in radiation, with values at 75% of the control radiation, resulting in greater final canopy biomass than the control (Figure 2a). Interestingly, the 50% radiation simulation also gives a higher yield than the 150% level, while the 25% level gives the lowest yield. Thus, radiation changes resulted in a nonlinear response on plant growth for maize as well as soybeans. As hypothesized by Chamedies et al. (1999) and Niyogi et al. (2004), a slight reduction in total radiation (dimming) may aid plant growth up to a certain point, while further reduction could have a negative impact on yield.

The evapotranspiration output for CERES-Maize (Figure 2d) is generally similar to the SOYGRO/CROPGRO output, except the values are typically larger. Again, evapotranspiration correlated with the radiation values.

4.3.2 Effect of Changes in Precipitation

Figure 3a shows soybean growth over time for different precipitation levels (25%, 50%, 75%, and 150% of the control). The highest yield occurs in the 150% precipitation run with more than 1300 kg ha^{-1} above the control run. The 75% precipitation is third, with a final crop biomass value that is almost 1500 units below the control, and is followed by the 50% value. The lowest yield occurs with the 25% precipitation output from the model. In the figure, the small dip in growth appears in mid-August (~day 71), with the 75% precipitation value falling close to 1500 units at the “end leaf” point, while the dip for the 50% precipitation occurs at “first seed.” Soybean yield is thus directly proportional to precipitation rates. Even though higher precipitation values were not tested, it would be intuitive that at some very high precipitation values, the crop yield would start to deplete as soils get water-logged.

As shown in Figure 3b, higher precipitation values also lead to higher water losses through ET. The increase in ET, however, does not compensate for the increase in precipitation. That is, precipitation changes are relative to the effective precipitation (precipitation – ET). Precipitation has interesting effects on the nitrogen concentration for the final day of the simulation (Figure 3c). An increase in precipitation resulted in a small decrease (~0.1%) in N, while decreases in precipitation varied by 0.7% below the control, and nitrogen concentrations decreased as the precipitation values increased from 25% to 75%.

CERES-Maize results for precipitation changes are similar to those obtained for CROPGRO. In Figures 3a and 3d, we also see trends similar to those in soybeans, with higher precipitation values indicating higher yields and ET values. Overall, precipitation changes appear to have a somewhat linear impact on the yield of the crops (soybeans and maize) as well as evapotranspiration and related responses. An important point to note is that excess precipitation would cause the yields to be lower. Since the present analysis focuses on the impact of alterations in individual versus simultaneous variable interactions on the simulated crop responses, this study only targets the changes in amounts of total precipitation during the growing season. No changes in the timing or intensity of rainfall occurred for each particular day that was considered. Such changes could modify the crop growth rate and alter the final yield results if these shifts occur at crucial stages of crop development (Mearns et al. 1996) and could be attempted in a future study.

4.3.3 Effect of Temperature Changes

The effect of ±1 and ±2ºC changes in the air temperature on the crop response was also studied (Figure 4a). Overall, temperature appeared to have a relatively smaller impact as compared to radiation and precipitation changes. This could also be due to the prescribed range (±2ºC is only about 10%). Overall, the soybean yield was dependent on temperature, with a preference for slightly cooler temperatures that then provided higher yields.

The prescribed temperature ranges also have a relatively minor effect on soybean ET values (Figure 4b). Even then, higher temperatures result in higher ET loss, as expected.

The results for CERES-Maize (Figure 4a, 4c) differ from the CROPGRO (for the temperature analysis). Both increased and decreased temperatures resulted in increased crop yields. The nonlinear temperature feedback may be due to the fact that temperature (growing degree-days: GDD) controls the rate of development in CERES-Maize. The CERES-Maize model only uses temperature and daylength to determine the rate of development; moisture and nutrient stresses have no effect.

As seen in Figure 7b, contrary to in soybean development, ET values are highest for the lowest temperatures and decrease with increasing temperatures. Thus ET, which is a combination of physical evaporation and plant transpiration, shows a nonlinear response to temperature changes in the case of maize.

Thus, systematic changes in temperature, precipitation, and radiation produce a variety of responses from crops. This indicates significant interactions among climate settings. In the following section, we will further synthesize the interactions explicitly.

4.3.4 Ensemble Analysis

One of the unique aspects of this study is its assessment of the effect of simultaneously variable changes on crop response. As shown in Figure 5, the interactions represent cases where climate change may create simultaneous changes in the three environmental variables. For example, in Figure 5, the highest soybean yield was for the pRpPmT run (i.e. 50% higher Radiation, 50% higher Precipitation and -2ºC for Temperature, as compared to the control). The mRpPmT, mRmPmT, and mRpPpT simulations exhibited relatively similar growth behavior throughout the lifetime of the plant and showed relatively similar, and average, yields.

Thus, the combinations of increased (decreased) radiation and high (low) precipitation generally yielded the highest (lowest) soybean yields. These interactions will be analyzed further in the following section.

The environmental changes resulting in high yields also show higher values of ET (Figure 6a, 6b). That is, higher radiation and precipitation changes resulted in higher ET. Precipitation has a discernible effect, with a linear negative response for ET. Moreover, the effect of precipitation variability is found in the ET values when both radiation and temperature are low, as the mRmPmT and mRpPmT cases demonstrate.

The ensemble plot (Figure 5) for CERES-Maize yields shows that two different cases, pRpPpT and mRpPmT, have the highest yields. Thus, precipitation is a dominant factor. Higher radiation values can synergistically interact to further increase the yields. The radiation-precipitation interaction appears to be nonlinear in that high precipitation – high radiation gives the highest yields, but low precipitation – low radiation combinations do not correspond to the lowest yields. Low precipitation – high radiation cases produce the lowest yields. The temperature interaction is more complex and could aid or reduce yield depending on the precipitation and radiation values, again suggesting active interactions in the system response. Leaf area expansion is controlled by GDD in combination with nitrogen and water stresses. Daily plant growth is calculated by converting intercepted PAR into plant dry matter using a crop-specific radiation use efficiency parameter (Jones et al. 2003). According to model specifications, changing the temperature will change the rate at which the crop grows and develops. For example, when the temperature was reduced, the crop developed more slowly (the dates of each of the growth stages occur later in the year) and the opposite occurred for increased temperatures. Increases or decreases in the temperature can result in higher yields if the timing of the moisture-sensitive growth stages is shifted so that these stages occur during precipitation-abundant periods and/or more favorable soil moisture conditions. If precipitation is evenly distributed during the growing season, then temperature changes may have little impact on yield.

The ET ensemble plots for CERES-Maize (Figure 6b) are comparable to Figure 6a for soybeans. As with soybeans, most values with high radiation result in high evapotranspiration losses. The high radiation (high precipitation) combinations lead to the highest ET values. One notable difference in the two crops is that for maize, low temperature settings tend to provide higher ET values. For example, mRmPmT leads to a higher ET than mRmPpT, and pRpPmT has higher ET than pRpPpT. The reasons for this will be reviewed further using interaction/factor separation plots discussed in the following section.

4.3.5 Factor Separation Analysis

The sensitivity runs identified various features associated with the effect of temperature, precipitation, and radiation changes on the soybean and maize yields as well as on the ET losses. The analysis was extended to understand the impact of simultaneous environmental changes (Figure 5 and 6). The results validate some conclusions regarding the role of variable change on crop responses (yield and ET) from the sensitivity study. However, different combinations suggest that the magnitude of thechange could also depend on the values of the other variables (Niyogi et al. 1999). These interactions can be extracted to point to an understanding of the effect and the vulnerability associated with climate change and its potential impact on crop systems. In this section we delineate these interactions.

In Figures 7 a,b (i.e., factor separation plots, Stein and Alpert 1993) the following information, as defined in the methodology, is included: (a) direct effect of individual variable changes, given as E_R,E_T, and E_P; (b) the effect of interactions between two variables (e.g. temperature and radiation changing simultaneously), given as E_{RT}, E_{PT}, and E_{RP}; and (c) the combined effect of all three variables simultaneously affecting the crop system, given as E_{RPT} (cf. Eq 2).

Figure 7a shows the factor separation plot for soybean yield. The double interaction of radiation and precipitation (ERP) has the largest positive effect, suggesting that increased radiation and precipitation would synergistically impact the yield. Double interactions between temperature and radiation (ERT), and temperature and precipitation (EPT) have relatively little effect. Interestingly, precipitation as a direct effect (EP) has little contribution towards yield, which apparently contradicts earlier findings in which precipitation was thought to be the single most important variable. The precipitation feedback is better illustrated via the interaction between precipitation and radiation, which was found to be more important. The triple interaction (ERPT) is also significant; however, this effect is smaller than the radiation-precipitation interaction. Thus, temperature changes can antagonistically interact with the dominant radiation-precipitation interaction. Radiation alone (E_R) can cause a significant direct effect, indicating that some reduction in radiation values could aid crop growth, and this can be further enhanced by higher precipitation and lower temperature values.

The factor separation results for soybean ET values are shown in Figure 8b. The ET shows a marked dependence on the radiation-precipitation (ERP) double interaction, which reaches more than 250 mm. This is physically expected since more precipitation could lead to higher soil moisture, and increased radiation produces higher ET rates. In the energy balance perspective, ET is a component of radiation, and thus the radiation direct effect (E_R) also shows up as a dominant term, along with the E_{RT} (radiation-temperature) double interaction.

The factor separation analysis of the maize yield is shown in Figure 7b. Radiation-precipitation interaction and radiation direct effect are the dominant terms. These results are similar to those obtained in the soybean studies. That is, the E_{RP} is strongly synergistic, and the E_R is a function of a negative feedback effect. Thus, up to a certain range, decreased radiation with increased precipitation provides the highest yields. The radiation feedback is nonlinear; i.e. relatively high and very low values could reduce the yield, and with average values, the yield could be high. Two differences are seen for the soybean and maize analyses. In maize, the triple interaction term that includes temperature is positive, as compared to the negative feedback in soybeans. Additionally, as compared to soybeans, maize shows significant interactions between radiation-temperature and temperature-feedback. Therefore, the temperature-feedback appears to be greater for maize than soybeans. Thus, unlike the soybean output, the maize output indicates that all R, P, T interactions make important contributions to maize growth. Such a scenario would lead to a more uncertain output that is less vulnerable to individual changes, but more responsive to the system as a whole.

The ET plots for soybeans (Figure 8a) and maize (Figure 8b) also show comparable differences and include more variability between individual runs throughout the simulation. Precipitation interaction with radiation (ERP) shows a marked increase up to Day 66 and then levels off with a slightly negative growth until Day 74, when at harvest time it increases dramatically to a final value of approximately 280 kg ha^{-1} of differential growth.

The ER achieves the second highest value with a constant linear increase from the onset of the simulation, but still lacks a strong influence on growth. The positive values of the radiation run reach close to 50mm. Both the ERT and the EP show little contribution; the precipitation-temperature interaction adds little or no contribution until Day 79. Although the ERT also makes a negligible contribution, it shows a slightly positive spike at Day 66, with a drop into the negative zone of the plot thereafter, a feature attributed to the ability of maize to retain moisture at higher temperatures. The variation in the temperature direct effect (ET) exhibits a negative relation and complements the ER effect, albeit a slightly weaker one. The triple interaction (ERPT) works as a negative feedback term throughout the factor separation plot. Though some variability exists in the interaction term, its final value is lower than -100mm. Thus, temperature variation, albeit small, appears to have significant effects for both crops in terms of evapotranspiration.

The interaction plots help identify the strategies and possible interactions that may occur between biosphere and atmosphere under a variety of climatic changes. The net effect can be considered a combination of main, or direct, effect and interaction effect. Therefore, these two components, when explicitly assessed, provide information on the potential vulnerabilities and the trajectories of possible impacts. A summary of the soybean and maize interaction runs is presented in Figure 9 a-f. This figure makes apparent that the impact of a variable change depends on other existing variable settings, which has potential implications for assessing the vulnerability of agricultural and other climate change impacts in future climate change assessments.

4.4 Conclusions

We developed a sensitivity and interaction analysis for climate variables on crop yield and ET for a C_3 (soybean) and C_4 (maize) crop. The results of our study indicate that solar radiation effects are nonlinear for the growth and development of vegetation. The highest yields were at 75% of the control solar radiation values and may suggest a partly cloudy or hazy day in which the plants could react positively, with an increase in yield as a result of diffuse radiation (Roderick and Farquhar, 2001, Niyogi et al., 2004). Also, precipitation changes are dominant drivers of plant productivity.

The reason for the 50% and 75% solar radiation simulation in the first stages of plant growth, which gradually tends to correlate, may be due to the way the plant reacts to radiation at different points during its lifetime. The lowered radiation values (dimming) better provide for a high growth rate during the first stages of development. Note that the leaf photosynthesis rate does not increase once radiation reaches a certain level; Boote et al. (1997) also confirmed this for our study site. In the model, the total radiation is spread out over the course of the day using a sine function. Then the proportion of leaves that either is sunlit or shaded is calculated each hour based on sun angle, and photosynthesis is calculated for both the sunlit and the shaded leaves. The modeled increase in biomass with decreased radiation is a function of two primary effects including the decreased radiation that, due to photosaturation, did not lower photosynthesis and the decrease in ET that resulted in less water stress and less maintenance respiration.

Very high or low incoming direct solar radiation also lowers growth yields. This effect is clearer when analyzing the multi-variable runs. The various interactions indicate that precipitation has an important effect on agricultural productivity and growth. This correlates with Wolf’s (2002a) findings, where water-stressed crops resulted in lower yields, regardless of any other variables or environmental settings involved. Prior model validation by Boote et al. (1996), Hansen et al. (1996), and Wang et al. (2001) also suggests that CROPGRO reliably detects these changes in water stress.

The sensitivity analysis showed that precipitation change is a dominant factor in plant growth. Analysis of the interaction plots showed, in particular, that crops benefit from interactions of precipitation with other variables, especially radiation. It is interesting to see that the 50% reduction of solar radiation and the 2°C decrease in mRpPmT show similar values in the runs, with a 50% increase in precipitation. The factor separation plot confirms the occurrence of this interaction by showing an almost negligible contribution to increases in precipitation alone (E_P). Overall, whenever a decrease in precipitation occurs, the yield falls well below the control value, mRmPmT being the exception to this rule. The factor separation plots complement this by showing that the radiation-precipitation interaction has the largest positive effect.

Temperature is another variable that affects plant development and yield. Given the range of change considered in this study, the simulated biomass variation was small. Still, it is important to point out that a decrease in the temperature increased the crop yield when both the runs included a negative change in temperature. The factor separation plots also show that an increase in temperature makes a moderately negative contribution to soybean yields.

When coupled with the other variables, temperature aided growth in some instances, as in the case with pRpPmT. The differences between pRpPmT and pRpPpT, as well as mRmPmT and mRmPpT, show that for soybean crops, lower temperatures could result in better yields. Other interactions, such as mRpPpT and mRpPmT, again highlight this effect since the simulation with the lower temperature resulted in a higher yield.

The precipitation data showed the expected linear behavior with higher amounts yielding larger crop biomass. Studies in Venezuela by Maytín et al. (1995) and in the United States by Brown and Rosenberg (1997) also found a similar sensitivity, with reduced yields for decreased precipitation and increased temperature.

The interaction analysis provides additional information than previously obtained in sensitivity studies. Indeed, many of the results on the effects of detailed feedback interactions are also confirmed. For example, high precipitation runs (pRpPpT and mRpPmT) tended to have higher values irrespective of radiation and temperature.

A difference found in this study arises from the E_{RT} case, which suggests that higher amounts of radiation and temperature would increase yield as the soybean crop simulations indicate. The interaction effect contributes significantly to the developments of the two types of vegetation modeled in this study, regardless of their photosynthetic mode (C_3 or C_4). These results were not shown in previous studies, such as Alexandrov and Hoogenboom (2000) and Magrín et al. (2002), where the radiation-temperature interaction was not assumed to have significant positive effects. The negative effect on yields found in this study for increases in radiation (E_R) and temperature (E_T) as direct effect are, however, supported by studies such as Maytín et al. (1995) and Brown and Rosenberg (1997).

The changes in evapotranspiration for the soybean and maize simulations indicate that increased direct solar radiation and precipitation could increase ET values, but the interaction term could lead to an inconsistent response. For instance, Iglesias (1994)showed that regional warming could increase evapotranspiration in maize simulations by as much as

18% above his control values. However, for some settings, increase in temperature for this study tended to lower ET values. This may correspond typically to lower precipitation conditions and could be due to simulated water stress as was also obtained in our analysis.

Results for the various nitrogen concentration outputs suggest that an increase in radiation and precipitation may cause levels of nitrogen to increase in plants. This is consistent with the results from Muschow and Sinclair (1994), which illustrated that under high fertility conditions, temperature and solar radiation explained the variation in yield between different environments, and that under low fertility conditions, mineralization of soil organic nitrogen was especially important in explaining yield among experiments.

Study results demonstrate how the multiple factors of solar radiation, precipitation, and temperature, when altered in a changed climate, can interact with each other in order to either reduce or enhance the growth and physiological response for crops such as soybeans and maize. These interactions can be somewhat difficult to understand at points where a plant's physiology, such as silking, grain filling, and sowing may become more important in order to provide a more generalized result. In general, radiation-precipitation interactions contribute significantly to crop growth. Further, maize (C_4 crop) was relatively less sensitive to temperature changes.

An important conclusion of this interaction-based study is that the effect of the variable change depends on the changes occurring in other variables within the Earth's atmospheric and soil system. This has important implications for the accurate assessment and modeling of the Earth's natural systems to atmospheric and organic climate change scenarios. Past studies which have considered one variable change at a time, such as warming or CO_2 doubling, can only show one-dimensional impacts and results.

Individual parameter change-based sensitivity and impact assessment identify the magnitude of impact on the crop yields, but do not explicitly identify the pathways and vulnerabilities of the impacts.

Results from these studies would benefit from reconsideration in light of other concurrent climate-change phenomena and should be adapted as just one possible scenario of a multi-parameter sensitivity analysis. The multiple-parameter change-based analysis indicates that crop yields and other growth-related processes show multiple vulnerabilities and sensitivities compared with the single variable studies. Therefore, LCLUC impact and climate variability studies should consider – in addition to the sensitivity scenarios – assessments based on ensemble analysis to synthesize feedbacks and explicitly identify the interactions among the variables in order to accurately assess the vulnerability to climate change. Current single-parameter sensitivity-based assessment can result in a flawed specification of the prominence of a variable change or an inaccurate identification of the manner in which climate change impacts natural processes as multi-parameter systems.

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Table 1. Definition of variables in multiple interaction simulations.

Expt	Variable Setting
mRmPmT	50% rad., 50% precip., -2C temp.
pRmPmT	150% rad., 50% precip., -2C temp.
mRpPmT	50% rad., 150% precip., -2C temp.
mRmPpT	50% rad., 50% precip., +2C temp.
pRpPmT	150% rad., 150% precip., -2C temp.
pRmPpT	150% rad., 50% precip., +2C temp.
mRpPpT	50% rad., 150% precip., +2C temp.
pRpPpT	150% rad., 150% precip., +2C temp.

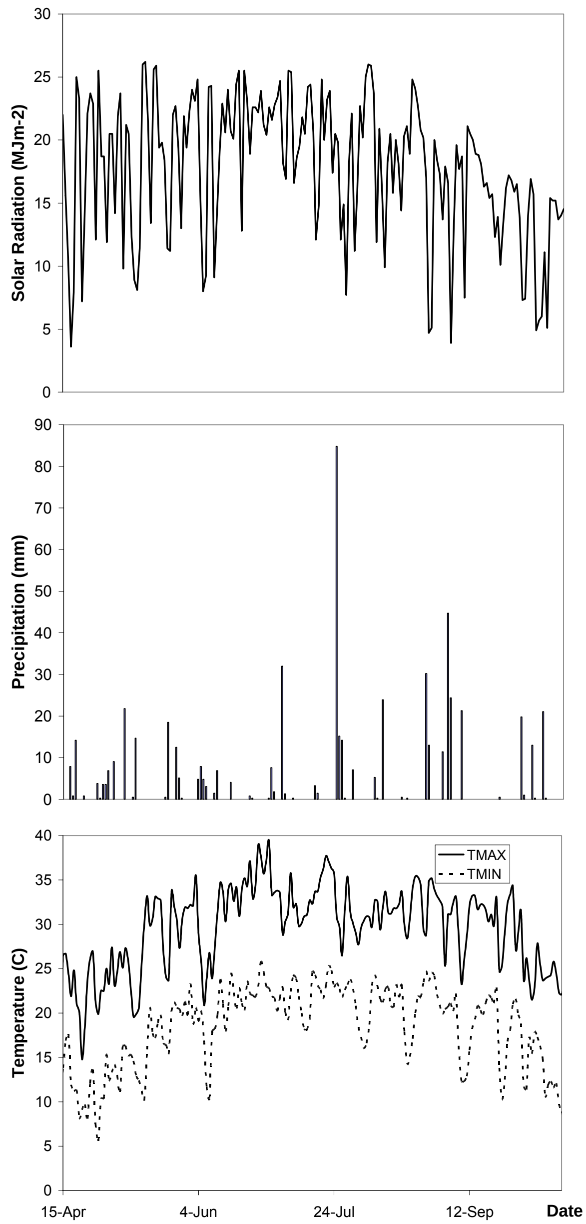

Figure1: Observed climate data for growing season (April 15th through October 15th). Solar radiation (MJ m-2 day-1) shown in the top plot, precipitation (rain – mm) in the middle, and Max. temp. (°C) (solid line), min. (dashed line) in the bottom plot.

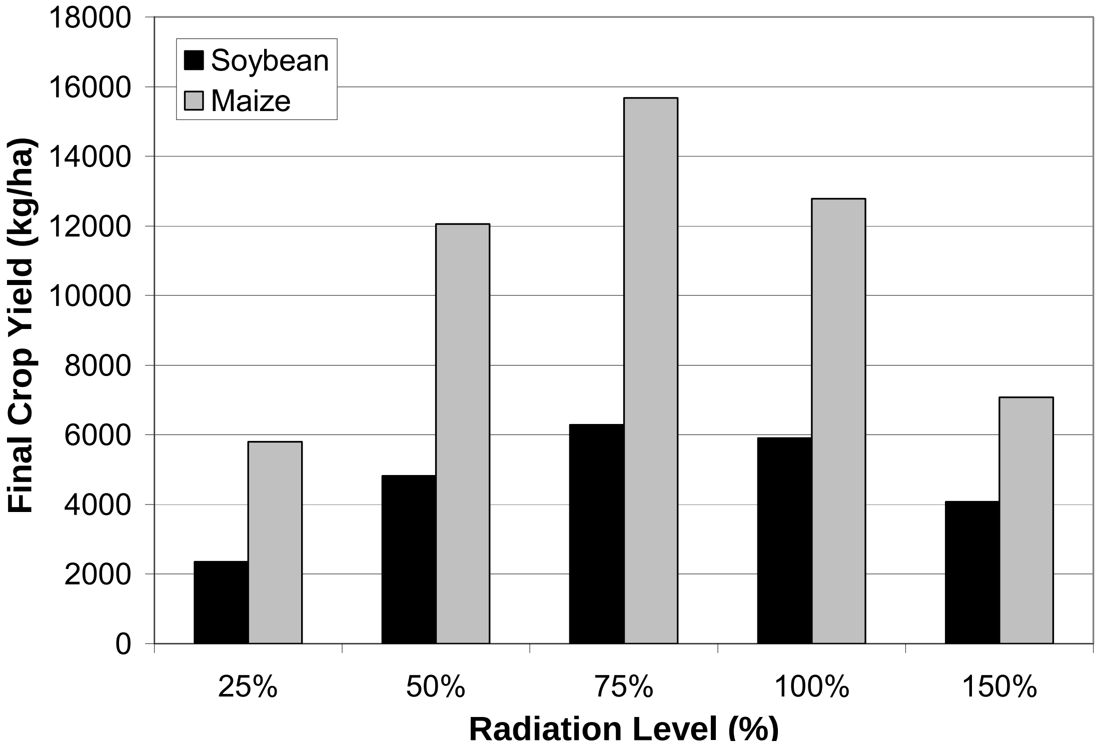

Figure 2a: Non-linear effects of radiation changes on soybean and maize yield (kg/ha). Higher values were obtained for 75% radiation simulation case indicating reductions in global radiation up to a point could aid crop yield and very high or very low values would have a negative effect.

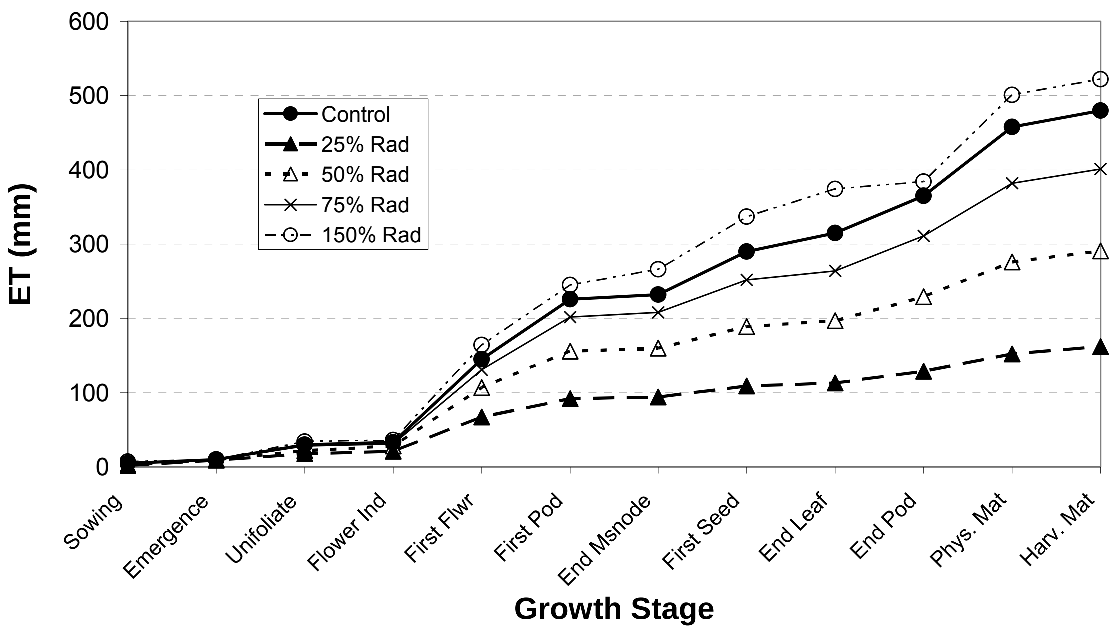

Figure 2b: Non-linear effects of various radiation changes on soybean ET (mm). Since ET can be considered a fraction of the incoming radiation, the values are proportional to radiation.

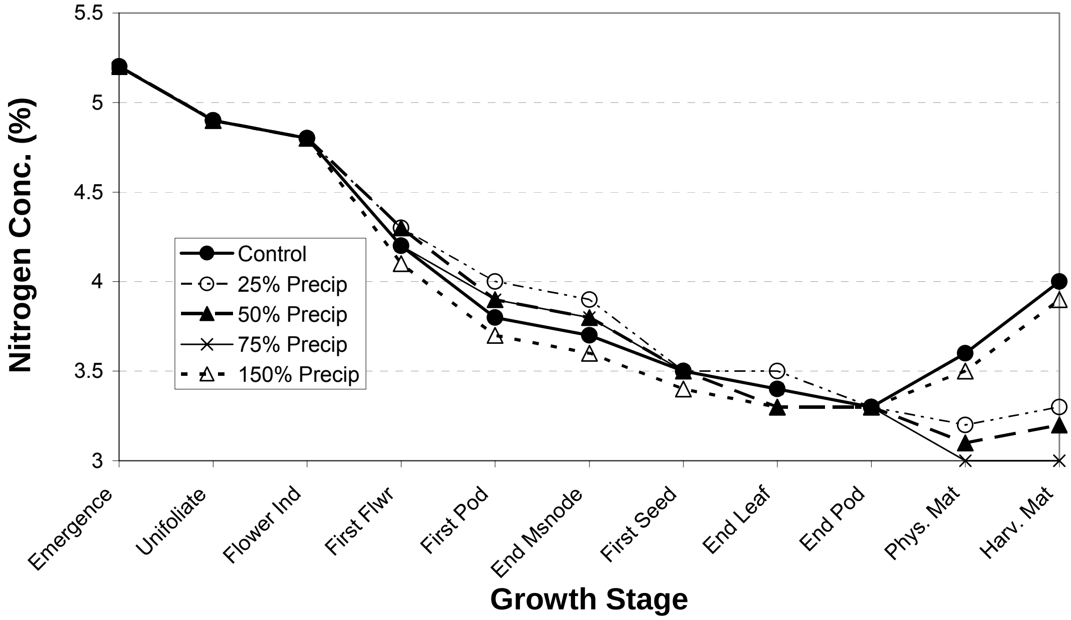

Figure 2c: Non-linear effects of various radiation changes on soy Nitrogen Concentration (%). Variation can be found most prominent at the "Harvest Maturity" stage, where the control value has the highest N concentration.

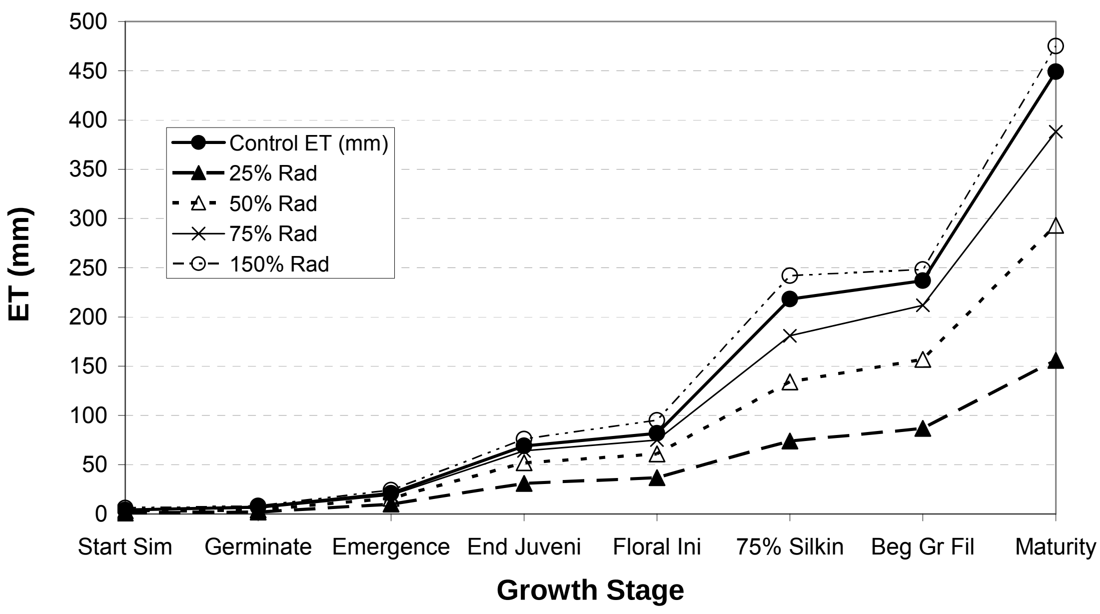

Figure 2d: Non-linear effects of various radiation changes on maize evapotranspiration. The same trend found for soy in Figure 2 is found for maize suggesting that the crop model picks up radiation effects on evapotranspiration similarly for different crops.

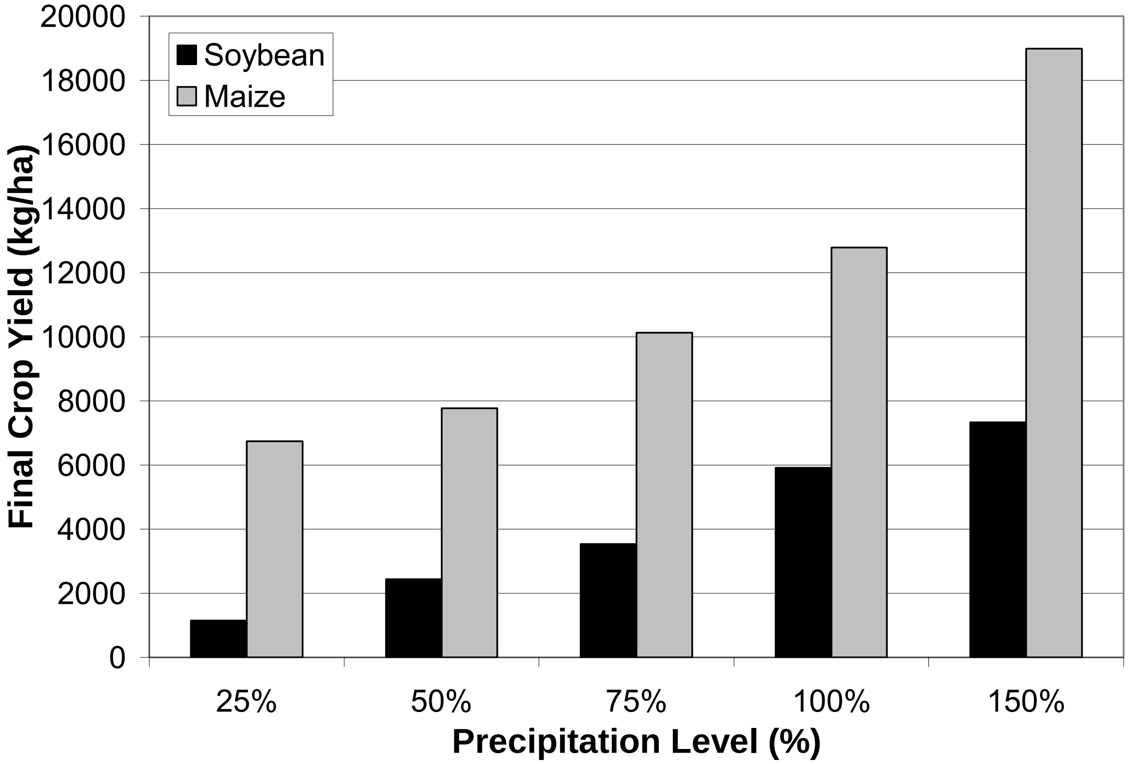

Figure 3a: Same as Figure 2a but for precipitation changes. The relationship is linear and higher values are shown for 150% precipitation simulation, suggesting the importance of higher levels of rain to crop yield.

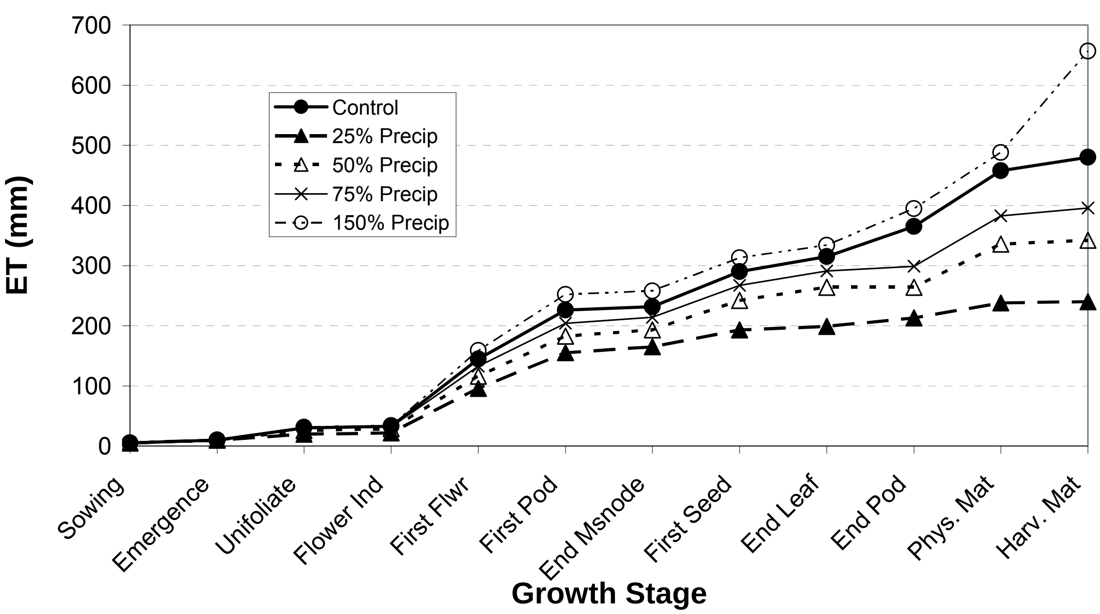

Figure 3b: Same as Figure 2b but for precipitation changes. Higher values are shown for 150% precipitation which could be a result of higher moisture.

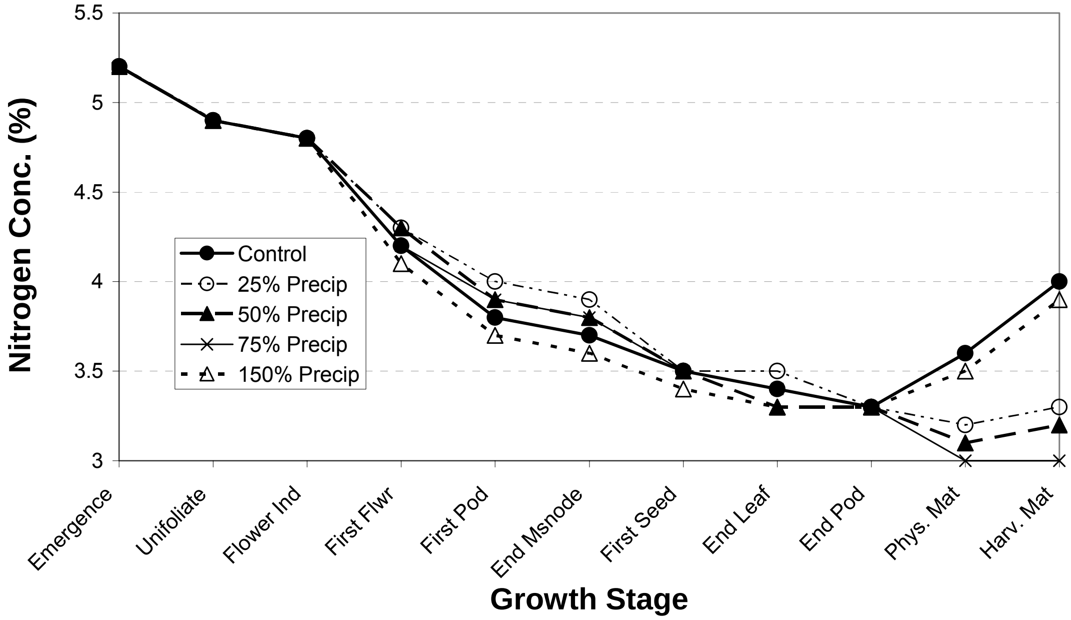

Figure 3c: Same as Figure 4 but for precipitation changes The Nitrogen concentration seems to increase with precipitation.

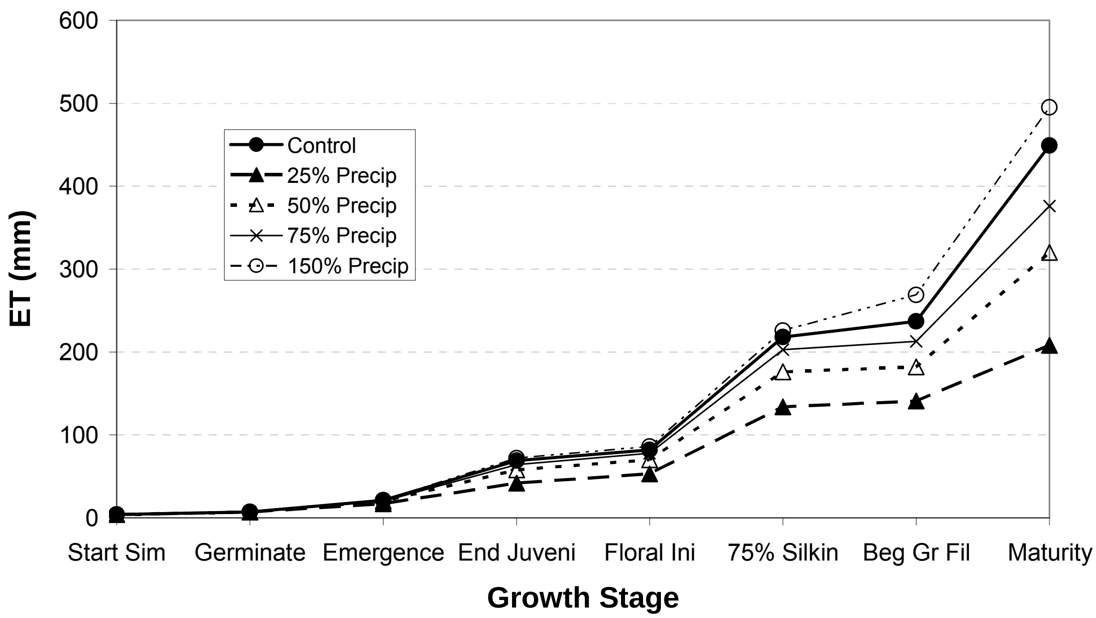

Figure 3d: Same as Figure 2d, but for precipitation changes. As with soy, the higher values are shown by the 150% precipitation simulation.

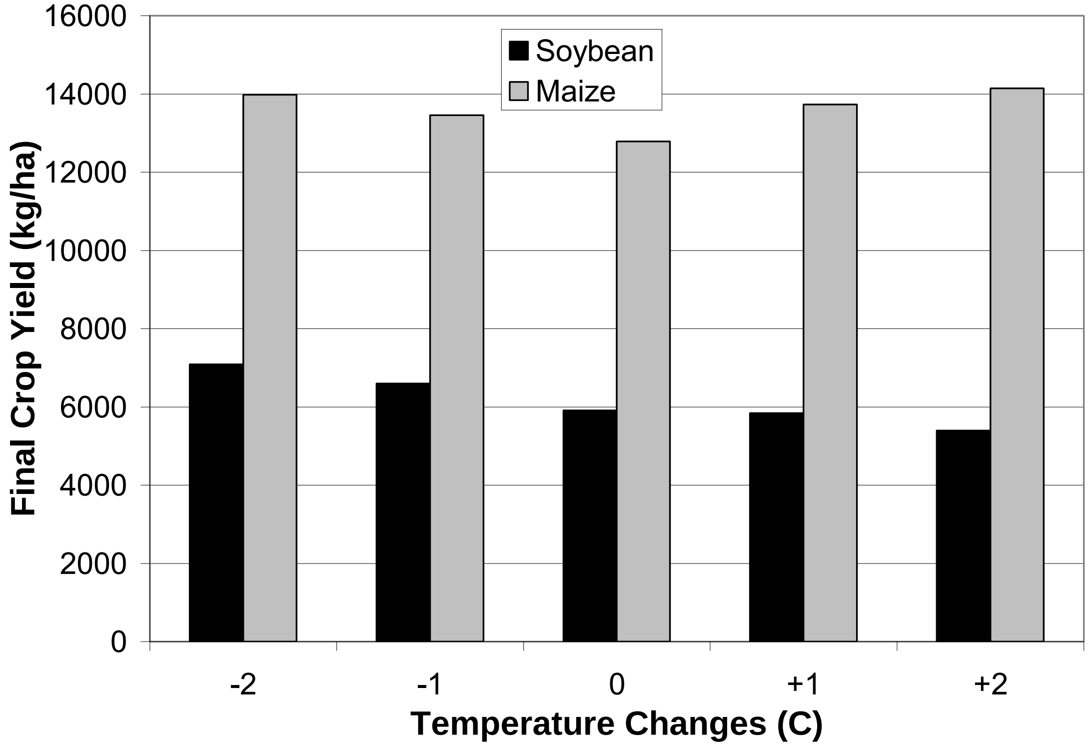

Figure 4a: Same as Figure 2a, but for temperature changes. In these simulations, cooler weather provided higher biomass yield for soybean. Temperature effects are smaller in magnitude for maize than that for soybean, although the further away from the control value (0) the better the final yield.

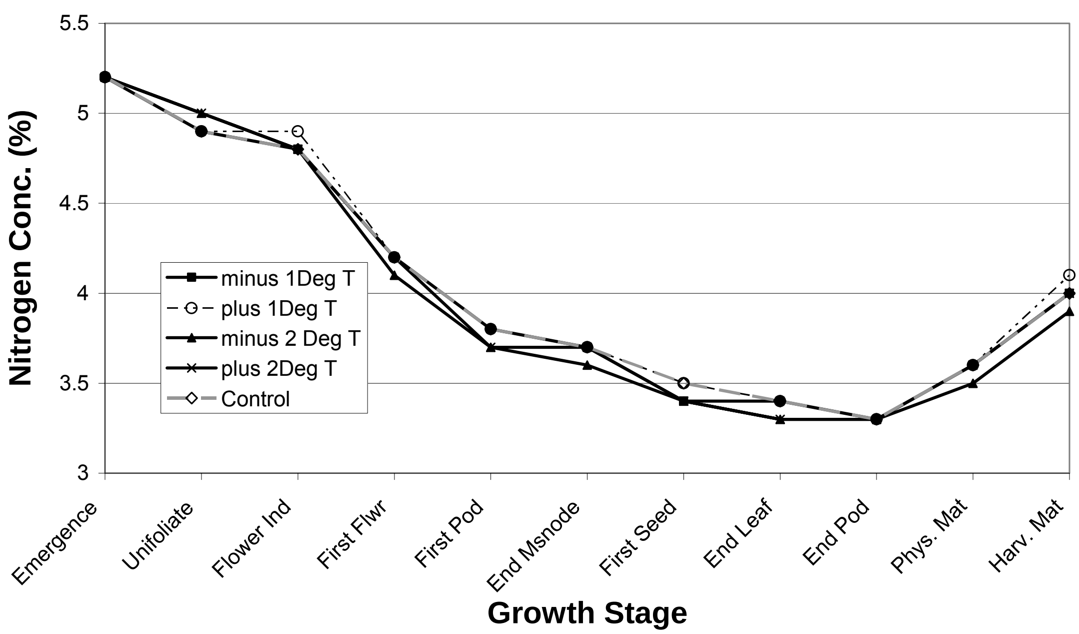

Figure 4b: Same as Figure 2c, but for temperature changes. There was little change due to temperatures.

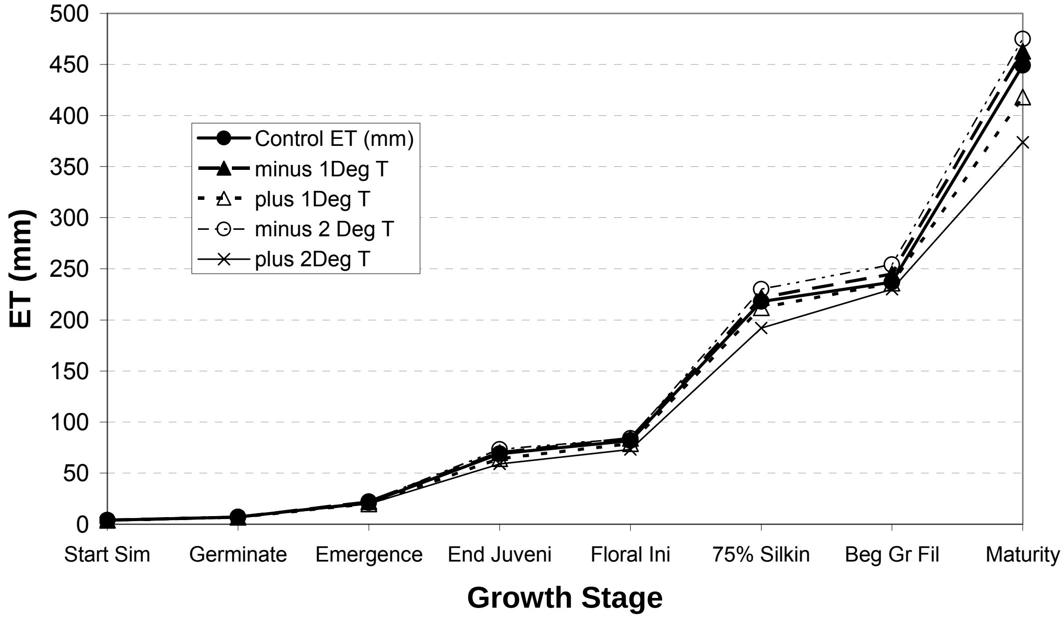

Figure 4c: Same as Figure 2d, but for Temperature changes. For Maize, cooler temperatures yielded higher ET values, which could be a soil moisture and humidity feedback than a temperature effect.

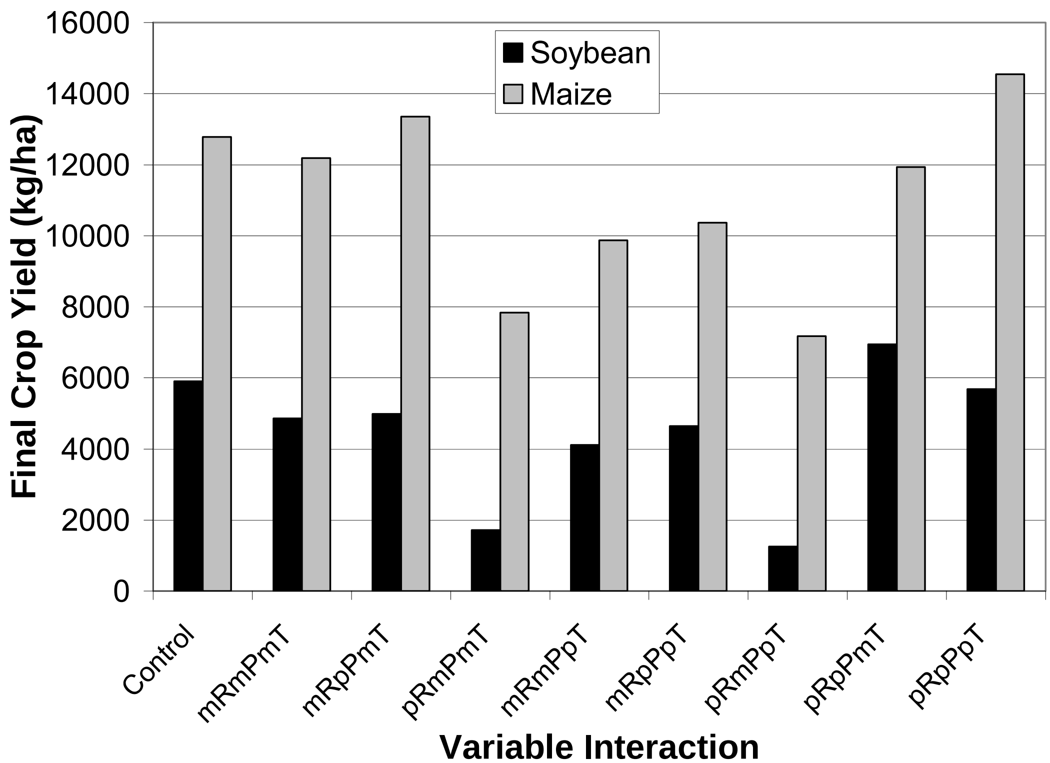

Figure 5: Non-linear effects of simultaneous climate change variable interactions on soybean final crop yield (kg/ha). Interactions involving increased radiation and precipitation with cooler temperatures (pRpPmT) yielded the largest values. In contrast, model runs involving increased radiation and lessened amounts of precipitation yielded the lowest values (pRmPmT, pRmPpT). Maize (gray) differs from soybean (black) in that the mRpPmT simulation also has a final biomass higher than the control values. pRpPpT remains the highest.

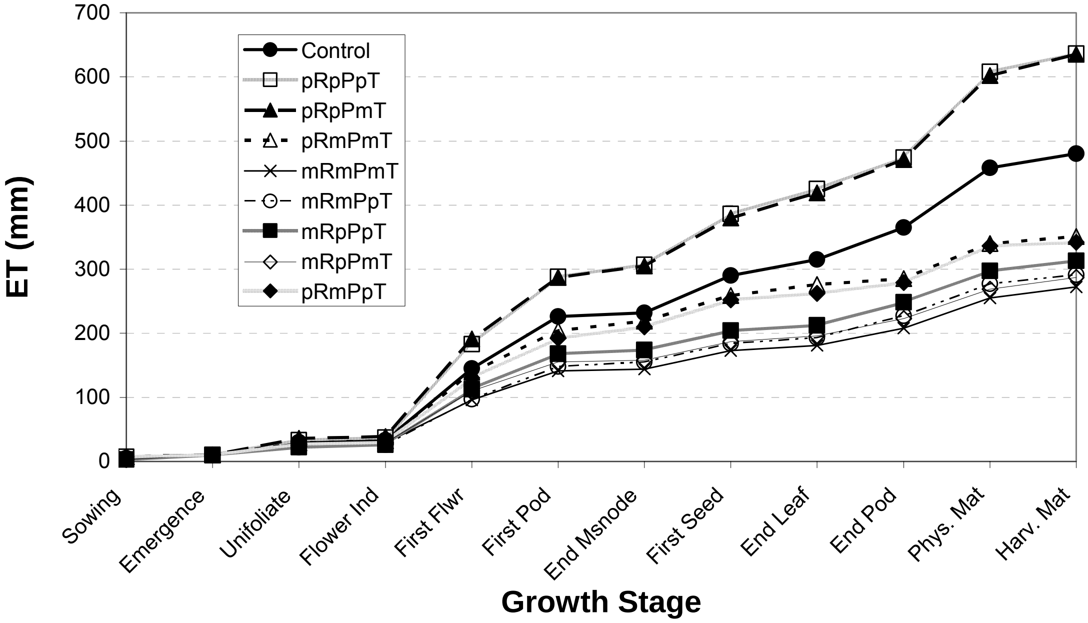

Figure 6a: Soybean crop evapotranspiration (mm). Interactions involving rises in radiation and precipitation with (pRpPmT, pRpPpT) yielded the largest values of ET. Lowered radiation values yielded smaller ET amounts though there was little variation among them (mRmPmT, mRmPpT, mRpPpT, mRpPmT).

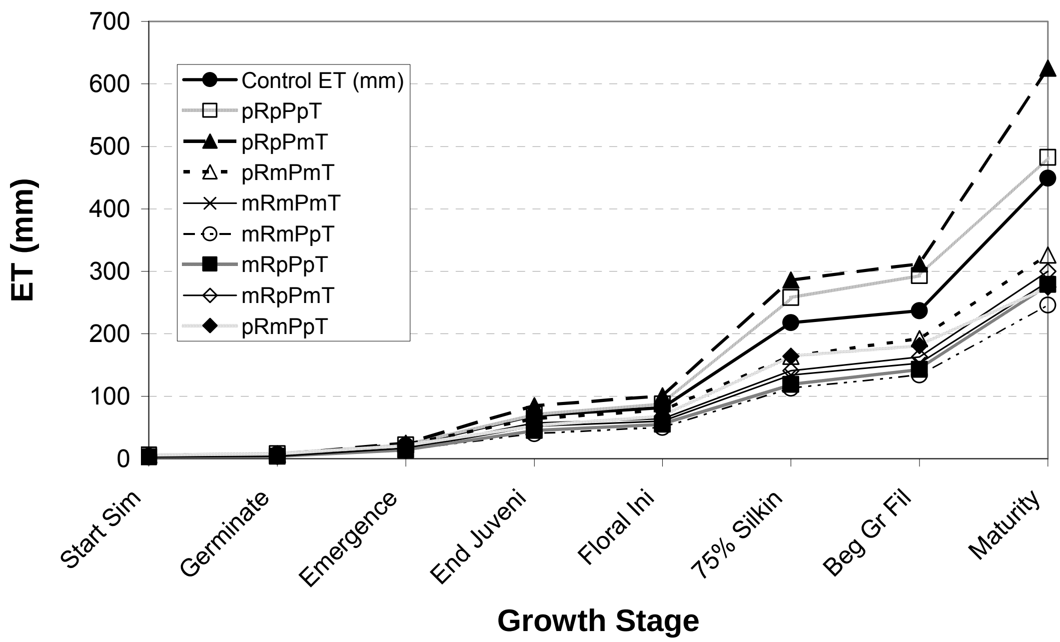

Figure 6b: Same as Figure 8b but for Maize crop. Maize differs from soy in that the pRpPmT is much higher than the control values as well as the triple positive interaction (pRpPpT). The lower temperature has a significant effect on ET.

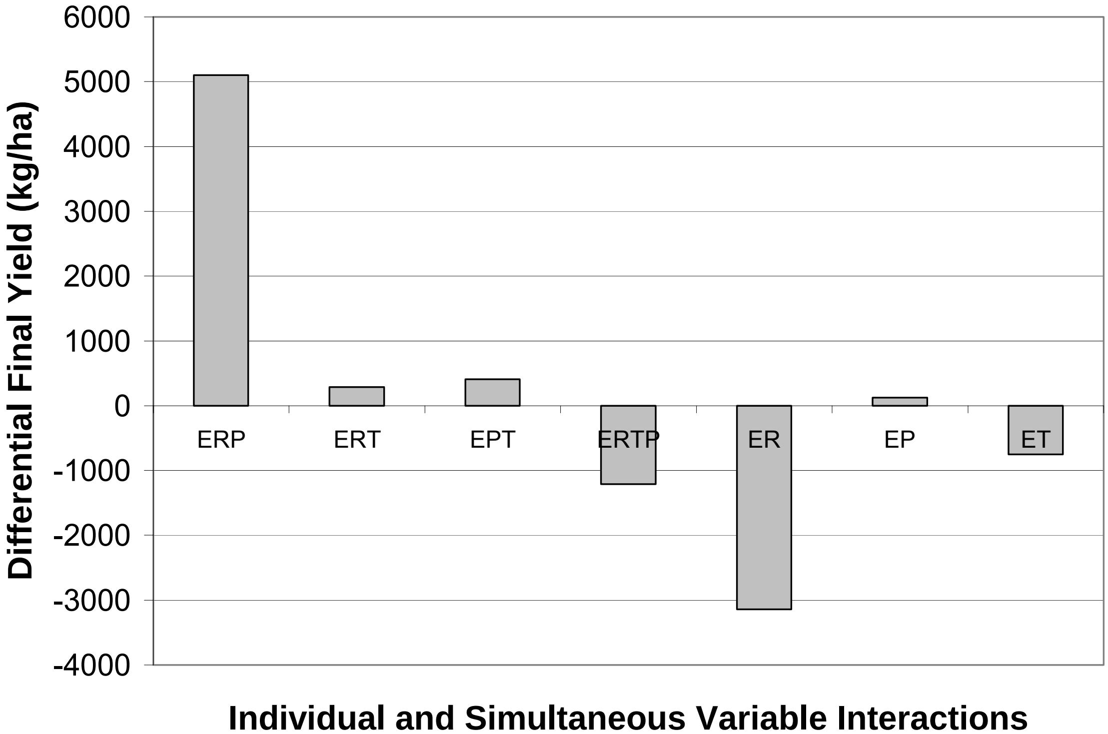

Figure 7a: Factor separation Plot for Soybean Crop Differential Yield (kg/ha). A marked trend exists for the radiation-precipitation (EpRpT) interaction to have the largest positive effects. Radiation contribution (EpR) alone gives the lowest differential yield while the triple interaction (EpRpPpT) and temperature (EpT) also appear to have significant negative effects.

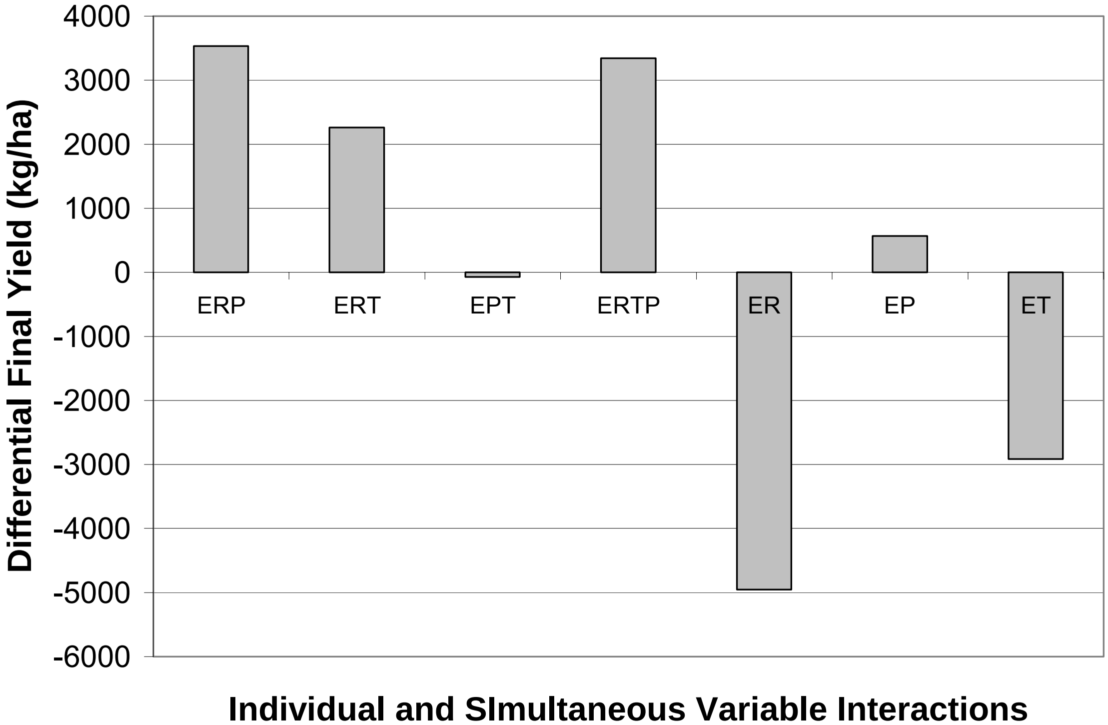

Figure 7b: Same as Figure 7a, but for maize.

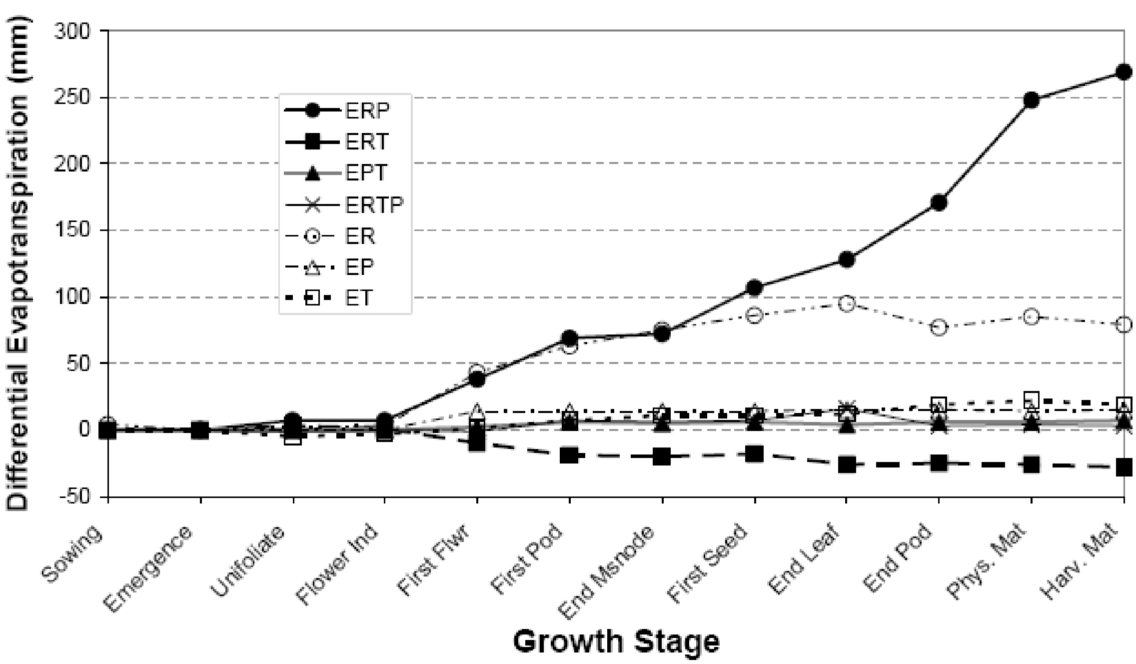

Figure 8a: Same as Figure 7a, except for soybean ET

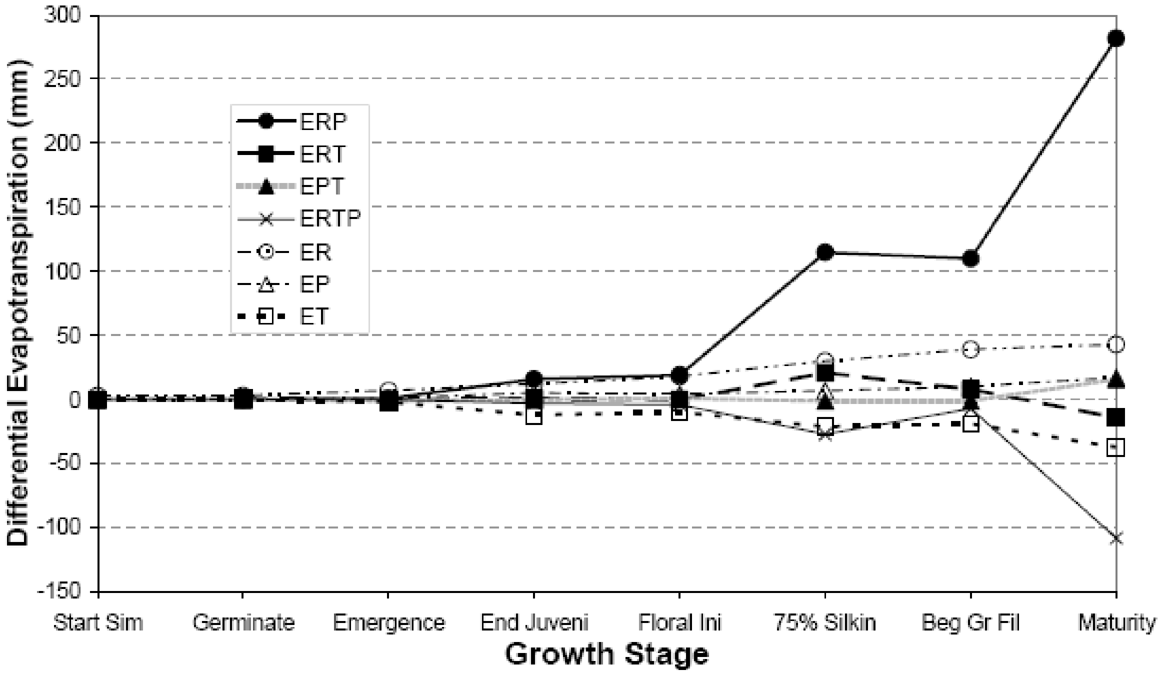

Figure 8b: Same as Figure 8a, but for maize differential ET (mm). The same general trend was found as in soybean, with the radiation-precipitation (EpRpP) interaction giving the highest differential ET found in this plot. Radiation (EpR) alone had a much less prominent positive effect while the triple interaction (EpRpPpT) gave the largest negative numbers.

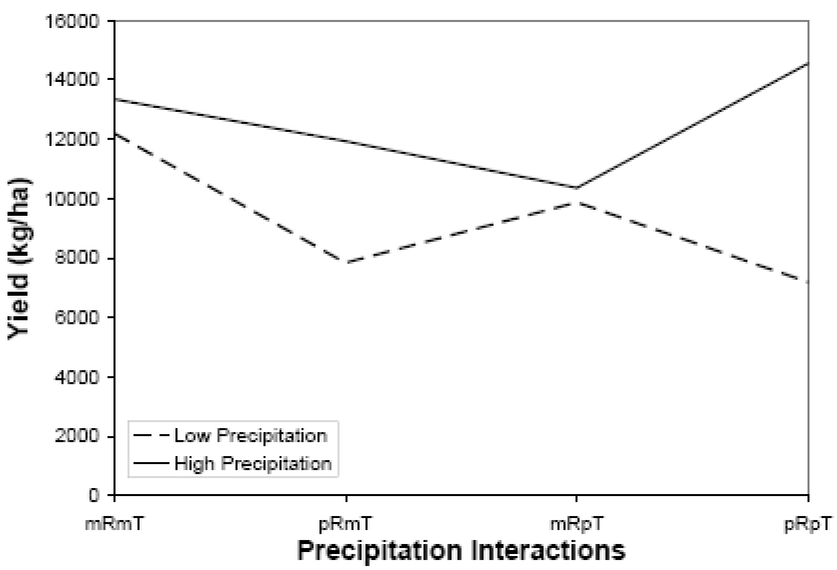

Figure 9a: Summary of interaction between radiation and temperature for high and low precipitation. settings results for soybean.

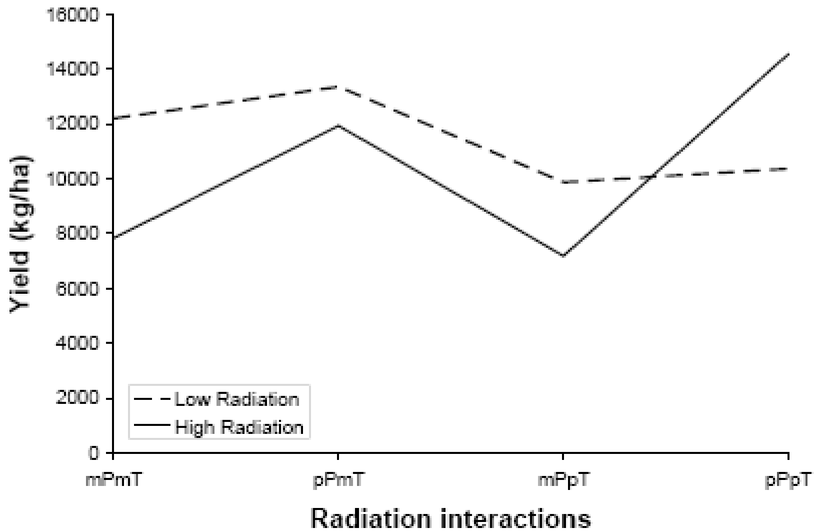

Figure 9b: Same as Figure 9a except for precipitation and temperature interactions under high and low radiation settings for soybean.

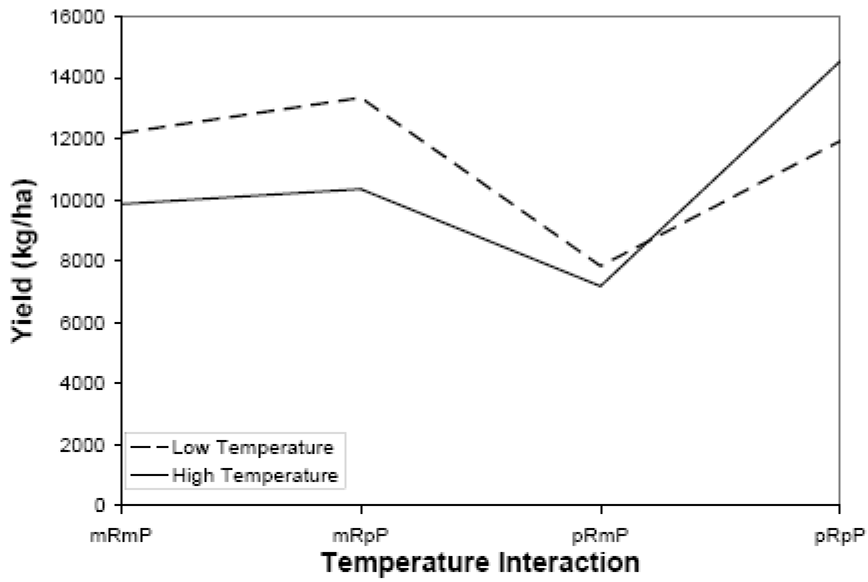

Figure 9c: Same as Figure 9a except for radiation and precipitation interactions under high and low temperature settings for soybean.

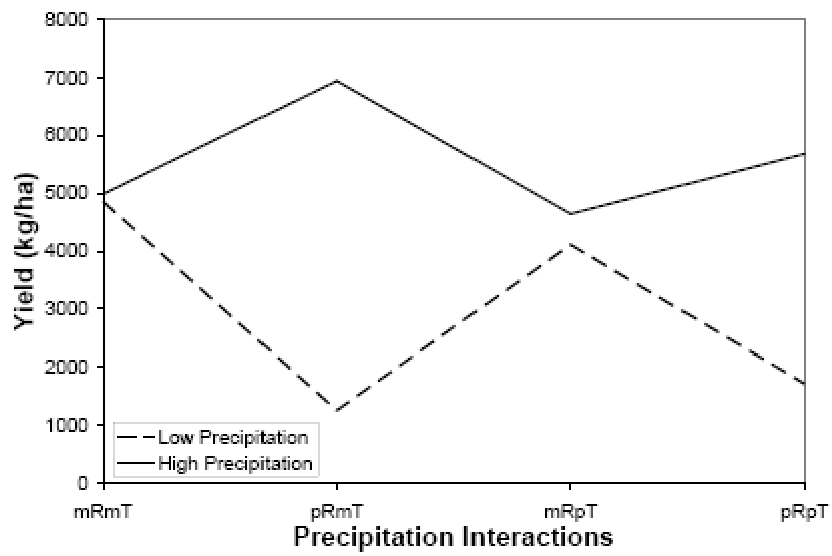

Figure 9d: Same as Figure 9a except for maize.

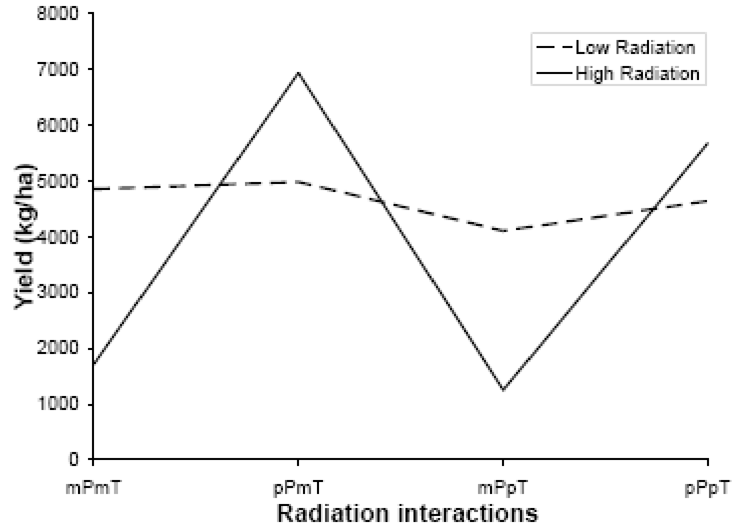

Figure 9e: Same as Figure 9b except for maize.

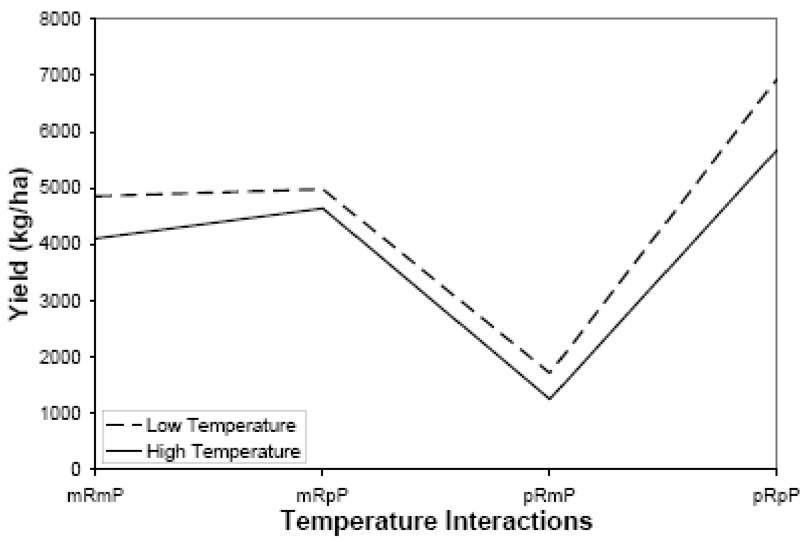

Figure 9f: Same as Figure 9c except for maize.

6. Summary and Conclusions

The study presented here is part of a broader study underway that seeks to understand the ability of crop modeling systems to be integrated within dynamic land surface modeling systems. Our approach was to use and evaluate the application of crop model – DSSAT (Decision Support System for Agrotechnology Transfer), which has models for soybean (CROPGRO/SOYGRO), peanut (CROPGRO/PNUTGRO), maize (CERES-Maize), wheat (CERES-wheat), etc. Analysis was conducted to test the crop model's response to multiple changes in the environment (e.g. CO_2, radiation, precipitation, temperature) and management (irrigation). We have focused on the soybean (CROPGRO /SOYGRO) and Maize (CERES-Maize) models. Three specific research tasks were developed to focus on integrating climate change information within crop modeling work.

The first part of the study was designed to identify the impact of climate change under higher CO_2 levels on soybean crop yields and performance. For the model CROPGRO-soybean, the field specific soil, plant specie (genotype), and management practice (tilling, fertilizer use, irrigation, etc) were provided to initially calibrate the model to accurately replicate the observations. Our first step in this study was to validate the CROPGRO (soybean) against enhanced CO_2 experimental data. Open chamber field experimental data (Booker et al., 2005) were available for soybean grown in ground under current and elevated (doubled) CO_2 conditions from ARS-USDA. The model was tested against these observations for the various conditions employed in the field experiment (ambient and enhanced levels of CO_2 in 1999 and 2000).

We found that the model accurately predicted yield and partitioning response to ambient conditions in the 1999 and 2000 seasons, as well as for the enhanced conditions in

2000. Predicted values for the 1999 season were significantly underestimated even though water stress was not present due to irrigation. Overall the model was able to replicate the observations within 10%. The model also lacked the ability to simulate the negative effects of ozone seen in the USDA-ARS field experiment. The inclusion of ozone in DSSAT would be beneficial by providing a more complete portrayal of air quality's effects on crops and helping to discern how interactions between O_3 and CO_2 may affect regional production.

Subsequently, we performed simulations to test the crop's sensitivity to modifications of the environment (temperature, rainfall, and radiation) under current as well as enriched CO_2 conditions. The effect of irrigation on the plant's response under current and elevated CO_2 conditions was also studied. Changes in climate variables were also applied to irrigation modification treatments.

We find that contributions to crop growth from solar radiation are dependent on the weather conditions experienced. Additional CO_2 also varied in its interaction with radiation according to seasonal conditions, suggesting that other interactions may be taking place in a season-specific manner when radiation levels are changed. It was also found that soybean crops in water-stressed conditions may favor diffuse radiation due to cloud cover or aerosols (Roderick and Farquhar 2001, Niyogi et al. 2004). We believe that crop modeling would be enhanced with the addition of diffuse radiation options to help characterize a plant's reaction to changes in atmospheric radiation.

Increasing levels of CO_2 tended to ameliorate the negative effects of water stress, and precipitation changes were only significant when irrigation negated the effects of water stress. Crop responses to temperature were found to be significant and varied according to water stress and CO_2 concentrations. We found that effect of an individual variable change depends largely on the changes occurring in other variables within the earth system, and that their interactions have significantly diverse outcomes when plants are exposed to irrigation or changes in atmospheric concentrations of CO_2.

In the second part of our study, the validated CROPGRO-soybean model (validated under both current and elevated CO_2 climate settings) was driven using 28 year regional climate model output from current as well as transient CO_2 experimental output (corresponding to the IPCC *RF* and *A2* scenarios, respectively).. Anomalies were adopted to bypass model biases using the difference between *A2* and *RF*. The anomalies were then added to the local observations for a 28 year period (1962-1989) and used to drive the crop model. The original RCM data with the *A2* scenarios had a significant warming trend and a relatively drier rainfall pattern near the end of the period. The model anomalies reduced the overestimated RCM precipitation and number of rainy days but did not retain the drying trend.

The observed and anomaly-based weather input simulations were carried out for four levels of CO_2 within the crop model corresponding to meteorology (and climate) that was representative of observed 1989, transient 1962 – 1989 and IPCC *A2* emission scenario for 2099, and transient 2072 – 2099. Additional simulations using original RCM data were also carried out at default DSSAT (1974) and IPCC *A2* 2099 CO_2 levels for comparison purposes. Overall, we found that CROPGRO-soybean responded positively to the use of model anomalies. The warming trend from the original RCM data had a significant negative impact on the yields which was further aggravated by the relative reduction in precipitation amounts. The lack of a clear warming trend in *AN* did not allow for this pattern to show up, suggesting further calibration is needed in anomaly calculations to retain a temperature trend that is potentially detrimental to soybean crops. The higher CO_2 levels (when introduced to the crop model) reversed the results in the original RCM data, providing increased crop yields as predicted by Unsworth and Hogsett (1996). The results from *AN* also showed that rising CO_2 levels will help soybean crops decrease water loss and usage (Unsworth and Hogsett, 1996; Serraj et al., 1999; Ferris et al., 1999). This portion of the analysis has shown how climate model data can be successfully applied to crop models to show the impact of climate change on biosphere-atmosphere interactions in terms of regional productivity. Our findings also show that changes in cultivar or planting date could help to take advantage of the concentrations of CO2 in the atmosphere while at the same time adjusting for the increasingly warmer weather. The results also suggest that the reciprocal effects from agricultural feedbacks under climate change can be significant, as exposed by the lower crop yields due to warmer, drier weather, which would cause lower transpiration rates and LAI. These variables should be considered in climate modeling, and this could be accomplished through the inclusion of crop models within dynamical land surface modeling systems.

For our third study, we used climate data for a field site at an agricultural research station in Clayton, NC to analyze the effect of individual versus simultaneous changes in R, P, and T on plant responses in a C_3 (soybean) and a C_4 (maize) plant. Once the model was calibrated, we provided 25 different climate (weather) scenarios to CROPGRO and CERES-Maize for different radiation levels, temperature values, and precipitation conditions. The scenarios used were derived from 1998 observed weather data for the Clayton site. This was achieved using the weather module included in DSSAT and CSDB (see appendices). The impact of these environmental changes on growth rate, yield, and water use were studied. Additional crop inputs such as crop age (date), biomass (kg /ha), ET (mm) and nitrogen levels were also considered to interpret the results and study possible feedbacks that may affect the atmosphere.

In the simulations, soybean was assumed to be in the ground on May 15^{th} with a harvest date of October 1^{st}. For maize the growing season ranged from April 15^{th} through the week of August 3^{rd}. Information on first flowering, harvesting, physical maturity, and crop maturity was collected to track the evolution of evapotranspiration throughout the period. The results were also analyzed using a statistical technique called Factor Separation method which allows us to understand the individual as well as simultaneous changes in radiation, temperature, and precipitation changes on potential crop yield and growth.

Our results using ensemble variable analysis and factor separation show that precipitation changes are dominant drivers of plant productivity, as has been suggested in previous studies (Rosenzweig and Tubiello, 1997; Iglesias et al., 1996) and as shown in a similar study by Wolf (2002a). The crops in this study also preferred lower radiation values, suggesting a partly cloudy or hazy condition are more favorable for plants as a result of diffuse radiation (Roderick and Farquhar 2001, Niyogi et al. 2004). The modeled increase in biomass in the presence of lower radiation values is a function of several season-specific aspects such as the decreased radiation that did not lower photosynthesis (because of the photosaturation), and decreases in ET which resulted in less water stress and lesser maintenance respiration.

Factor separation shows that the interaction between precipitation and radiation is dominant. Another interesting finding is that contributions to growth from precipitation alone are clearly surpassed by those from the radiation-precipitation interaction. Temperature alone did not provide a significant contribution to growth either, but the results do show that soybean prefers slightly cooler conditions than the observed for higher biomass. One unexpected result was the relative importance that the radiation-temperature interaction had for both types of crop. Previous studies stated that there was little contribution made by this interaction (Alexandrov and Hoogenboom (2000) and Magrín et al. (2002)). We suggest that this may be due to the specific conditions experienced by the plants on this particular season (e.g. timing of precipitation events), and further testing on a longer time scale is needed to ascertain the relative effect that this variable interaction has on soybean and maize. The results also show that nitrogen concentrations were increased by higher amounts of radiation and precipitation, and correlates with temperature and solar radiation explaining the variation in yield in high fertility conditions. Our findings also coincide with results from Muschow & Sinclair (1994), where under low fertility conditions, mineralization of soil organic nitrogen was especially important in explaining yield among experiments.

Direct crop interactions with the atmosphere can be seen in the evapotranspiration analysis. We found that increased solar radiation and precipitation would cause higher ET values, although their interaction could lead to inconsistent responses by the crops. One such case takes place where the direct contribution from temperature tends to lower ET values. Previous studies suggest that the opposite usually occurs with maize fields (Iglesias, 1994), and we suspect that it in our simulation this could be due to lower precipitation.

The study results presented here suggest that there is good potential in the use of crop models within dynamical land surface modeling systems for current and doubled CO_2 scenarios. The climate variable testing used with the crop model may help identify potential problems that need to be addressed within the crop modeling system. This approach, as well as the coupling with the RCM may also aid in determining the types of changes that need to be made within RCMs to create agricultural level rainfall predictions. Interactive aspects such as evapotranspiration, LAI, seasonal evolution of soil moisture due to crop water usage, and albedo are important outputs that could influence mesoscale modeling, as well as regional and global climate models. We have shown that the interaction between croplands and the atmosphere can determine regional productivity as well as regional changes in climate. Additional considerations for ozone as well as process-level formulations that include changes in diffuse radiation to account for radiation changes are important missing components which need to be added into the model. Such additions will help improve the crop model's usability by further expanding it into simulations analyzing the effects of air quality.

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6. APPENDICES

6.1. Using DSSAT

6.1.1 DSSAT Data Requirements

ICASA's DSSAT (Decision Support System for Agrotechnology Transfer) crop model package has certain requirements in order to properly simulate crops. For this experiment, we have chosen to used CSDB (Crop Simulation DataBase, Beta Version; Buol et al., 2002), which provides easier user interface and additional options that allow for faster experimental setup. In DSSAT, as well as CSDB, one must provide the cultivar (race or variety of a plant) and group; soil type; descriptions of the field (location, etc.); planting dates, row spacing, depth, distribution, population at seeding and emergence, and planting method (transplant, seed, pregerminated seed, nursey, unknown); irrigation setup; environmental conditions (yearly weather information). These may be accessed through the choices included after opening the database on the first window. Modifications, additions, and setup can also be achieved through the treatments option (to be discussed in section 6.4).

6.1.2 Weather Module

Environmental conditions can be input into the model through the weather option on the main window of CSDB. This option allows for the use of a variety of experiments to take place, such as sensitivity treatments, prognostic treatments (climate model data), and validation studies (comparison of model output and field study results). In this window, you can create a new weather file or open an existing one. If you choose to open, a window will appear that shows you different locations that include previously generated experiments. If you choose "new," a window will open that allows you to choose from a variety of locations that had been created either by you or those that are included in the model. Locations may be managed in the “locations/sites” module accessible in the first window of CSDB. There you may access the available locations and sites, or add new ones by providing the required information: latitude, longitude, elevation, etc. Note that only latitude and longitude are necessary, but you may wish to add the others for reference purposes.

DSSAT requires the inclusion of the following variables for proper simulation: minimum and maximum daily temperatures (°C), daily precipitation totals (mm), and daily total solar radiation* (MJ m^{-2} day^{-1}). Other variables such as dewpoint (°C), photosynthetic active radiation (moles m^{-2} day^{-1}), and wind speed (km day^{-1}) can also be added but are not necessary since they incur little change. All of these variables are listed as headers in separate columns in the weather module spreadsheet. The module separates the daily environmental values into the 12 months of the year (each in its own window accessible through tabs at the bottom of the page) and a year summary in a final window that includes yearly and monthly totals and averages for all variables.

The weather module allows for the import of data from the weather files (.WTH) included in the database, as well as notepad (.txt) and MS Excel (.xls) files. Importing data from MS Excel files and notepad files requires copying them into the weather module window itself. It is not necessary to copy data month by month from your MS Excel file; you may copy an entire year into the first page (January) and it will ask if you want to paste the excess data into the other monthly tables. It is advisable to double-check data for minor mistakes such as a higher minimum temperature than the maximum for the same day and negative values of solar radiation and precipitation.

*See section 6.1.3

Once you have finished creating the weather file you have the option to view the weather information in the form of plots by clicking on “graph” at the top of the page. This allows for the interpretation of weather patterns that may affect the crops during the simulated season.

6.1.3 Calculation of Solar Radiation

Solar radiation (*Rs*) is an important variable needed for crop simulation as well as other areas such as meteorology, hydrology, and soil physics. It has proven to be a difficult variable to work with in the past because historical weather data often lack *Rs* measurements (Ball et al, 2004; Richardson and Reddy, 2004). Therefore, several ways to calculate/estimate it have been derived. Our work with crop simulation requires daily solar radiation input along with precipitation and min/max temperatures. Such information was not present for our studies using field data from 1999 and 2000 as well as the RCM simulations.

Radiation estimates for historical weather may be obtained by calculating *Rs* using either a site-specific radiation model or a mechanistic prediction model. We have chosen to use the mechanistic model equations that appear in Hargreaves and Samani (HS, 1986) and are reviewed by Ball et al (2004) along with two forms of the Bristow–Campbell model, described by Thornton and Running (TR) and Weiss et al (WS). Richardson and Reddy (2004) also found that this particular scheme was relatively accurate in predicting both *Rs* and yields. They found that estimation accuracy depended on the type of approximation used, temporal-averaging schemes, and location.

Ball et al (2004) found that HS had small root mean square errors for the regression of predicted vs. observed *Rs* and that the TR model had a slight superiority over the HS model.

Due to the constraints of this study, the HS model was preferred because it utilizes the latitude (l), julian day (d), and min/max temperatures (tm, tx) for the day. The equation also uses solar declination (DEC), sunset hour angle (OM), distance between earth and sun for a given day (RAES) and extraterrestrial radiation (RA). The calculated *Rs* will be calculated in MJ/m^2, which is the required unit in DSSAT. Below are listed the equations used by HS to acquire *Rs*:

$$DEC = 0.40876(\cos(0.0172142(d+10))) \tag{1}$$

$$OM = A\cos(-\tan(l(0.0174533))\times\tan(DEC))) \tag{2}$$

$$RAES = 1.00028-(0.03269\times\cos(0.0172142\times(d+10))) \tag{3}$$

$$RA\ (langleys) = 916.732\times(OM\times(\sin(l\times0.0174533))\times\sin(DEC)+\cos(l\times0.0174533)\times\cos(DEC)\times\sin(OM)))/RA \tag{4}$$

$$Rs\ (MJ/m^2) = 0.007133\times RA\times((tx-tm)\text{^}0.5) \tag{5}$$

6.1.4 Generating and modifying an experiment: Treatments

The "Treatments" option in the main page of DSSAT contains the ability to create new experiments and modify existing ones. You can choose to create an experiment or a treatment within an experiment. At this point, CSDB has been configured only for maize and soybean, but you may contact the model developer (Greg Buol) for more information. To create treatments using CERES-Maize (Jones and Kiniry, 1986; Hoogenboom et al., 1994; Ritchie et al., 1998) or CROPGRO/SOYGRO (Hoogenboom et al., 1992, 1994; Boote et al., 1998), choose the desired crop and click on one of the experiments in the subdirectory (this may bean existing one or one you have just created). You are asked for some basic information describing the new treatment. You may also copy, delete, edit, remove treatments from the experiment, and add a treatment to the simulation group.

The information required to create a treatment is the basic information listed in section 6.1, plus the site, weather site (may be different from site), crop/cultivar, and the selected experiment. You may click on any existing treatment to highlight it and its information will appear in the right hand section of the screen. Here you will be able to see the name of the treatment, notes, an overview with basic treatment information, and a section called "data" that includes several folder icons. Here you may choose to view/reconfigure specific information of a particular treatment. For instance, the cultivar icon will open a new window that shows the type of crop, the cultivar coefficient, and the treatment cultivar name being used. Related treatments using the same general information are shown at the top of the window. If you choose to change an item, you will have two choices: set or apply. Choosing set will employ the changes on this particular treatment, while applying them will change it for all related treatments as well.

Other options that may be accessed in the "data" section include "environmental modification," "field," "planting," and "simulation control." There are several other options included, but usually only the ones that have a green check mark on top are operational. As with the "cultivar" option, the other options also allow for reconfiguring the treatment as desired. For example, using the "field" option allows you to change to a different field or location. Planting specifics can also be manipulated under the "planting" option.

The "environmental modifications" option allows for changes in weather conditions on a daily or yearly basis by clicking on "Tabular Environmental Modifications Data." This powerful tool lets you modify variables such as day length, precipitation, temperature, solar radiation, carbon dioxide amounts, dewpoint, and wind speed. Here, you specify a value you wish to change to or modify with (addition, subtraction, multiplication, and replacement).

Another equally important tool is the “simulation controls” option. This tool allows for the modification of important variables such as irrigation, chemical routines (nitrogen, phosphate, etc.), light interception and photosynthesis calculations, among others. It also gives you the option to select the contents and layout of model output. The “summary” option allows you to record observational data for comparison with model output.

To start the simulation, you must click on the “Simulation” option at the top of the page. A separate window will open where you will be able to choose to run a highlighted treatment at the set location, or to select a weather year from *any* location on *any year*. You can also choose whether you want to simulate a crop for a single year or a selected number of years. Finally, the next window asks for the types of reports to be generated (general, summary) as well as the detailed reports (includes options such as growth, carbon, water, nitrogen, etc.) At this point you may start the simulation.

The outputs can be viewed be clicking on the “Results” option at the top of the page. The chosen reports are given in text format and can be viewed in their entiretywithin the program itself and as a text file once it is saved. CSDB and DSSAT also allow for graphical portrayals of the results by clicking on “seasonal graphics” or “summary graphics.” Seasonal graphics include parameters such as weather, growth, soil temperature, etc. The summary graphics allow for graphical comparisons between the model results (yields, water balance, etc.) and those from the observations included in the “summary” option.

6.2 Chapter 2 Model Calibration

6.2.1 Extended Chapter 2 Methodology

During the initial calibration process for the 1999 Ambient CO2 field experiment data (Booker et al., 2005), we adjusted some of the coefficients (CARBON AND NITROGEN MINING PARAMETERS) in the species file to get maximum agreement between the model and the observed data. Originally, the model was either incorrectly partitioning dry matter between plant parts (leaf, stem, root, or pods) or incorrectly handling soluble and structural carbohydrate in the stems. We suggested that the model needed to place more soluble carbohydrate into the stems and less structural. This would allow the stem weight to drop lower at the end of the season as the soluble carbohydrate is remobilized to aid in seed development. Thus, the two parameters in the species file (SBGRO040.SPE file in the genotype directory under the DSSAT4 directory) controlling soluble carbohydrate were modified. This change had negative repercussions for the Enhanced 1999 CO2 model runs by giving uncharacteristically low yield levels. Interestingly, the simulations for 2000 did not change in this manner and remained in good agreement with the field experiment data.

Further, the soil used in the initial validation simulations was Norfolk sandy clay loam, where the field experiment had specified Appling sandy clay loam. This would have implications in how the model handled water stress and needed to be changed in order to correctly simulate the field experiment data. We have redone the simulations using the correct soil.

During initial calibration, we found that crop yields were markedly lower than the field experiment, and another factor was adjusted to circumvent this problem. CROPGRO was developed to simulate the growth of field-grown soybeans and not soybeans grown in open-top chambers. We initially found that simulated yields for 1999 ambient CO2 were way too low when he first looked at it, even assuming no water stress and no nitrogen stress. We believe that this may be due to a severe "border" effect on photosynthesis, where plants on the edges of a field are able to intercept more light at lower angles than the rest because there is less shading from other plants. The chambers in the field experiment were small and were not surrounded by other rows of soybeans. A significant amount of extra light was probably reaching the plants so that they had much higher rates of photosynthesis and growth than normal.

The simplest way to counter this was just to adjust the "soil fertility factor" (SLPF) for the soil profile. This parameter is normally used to adjust for field to field variability in fertility. CROPGRO assumes that potassium, calcium, phosphorous, and all trace minerals are non-limiting and the model does not simulate the addition of these through fertilizer or uptake or even use of these minerals in creating biomass. We thus increased SLPF in the soil for Appling sandy loam. We increased the value from its normal value of 1.0 to 1.27. Without this increase the simulated yields and other plant part dry weights are significantly lower than those measured by Booker et al. (2005). The model has thus been artificially adjusted to simulate open-top chamber experiments and *not* an open field. We have decided to continue with the adjusted value and assume that the changes in our sensitivity analysis are for an open-top chamber experiment and not an open field. Further simulations will be carried out to acquire open field conditions. We have adjusted and compared this value for our non-irrigated versions of the 1999 ambient and enhanced experiments to see what the effects of water stress may be.

6.2.2 Results and Conclusions

Our results show a significant change in the approximations given by CROPGRO for the open-top chamber data. Comparing figure 1 to figure 2 we may discern that the 1999 Enhanced CO2 is considerably higher and closer to the observed data for yield (seed weight) and pod weight although still exhibiting underestimation. The 1999 Ambient CO2 also underestimates the observed but is still approximating the field experiment results, although not with as high an accuracy as the altered species run that caused the problems with the earlier simulations.

In figure 3 we show what may have happened if we had used the default SLPF value (1) of the Appling sandy loam to simulate the experimental data. Serious underestimation is visible in this plot, suggesting that the border effect in the observed may indeed be the cause for the higher amounts. In figure 4 we compare the non-irrigated simulations using both SLPF set at 1 and set at 1.27. Again we see much lower values using the original setting of SLPF with a significant difference in the weights of stem, pod and seeds.

The 2000 simulations (see figs 5 and 6) exhibited interesting results in that the majority of the changes occurred in the ambient seed and pod weights through slight underestimation. Stem weight was also much closer in the new runs with the original species and correct soil data. Other than these points there wasn’t much difference between the two sets of simulations. All values were underestimated when SLPF was set at 1 in Figure 7 just as they had in figure 3 for 1999. Figure 8 also showed the same characteristically significant lower values of the weights in SLPF set at 1 for Appling in non-irrigated field conditions.

In our sensitivity analysis we find that the same general patterns hold true for radiation in the original species file with Appling sandy loam soil (see figs 9 and 10), where water stress determines how radiation will affect the crop regardless of CO2 levels. The non-irrigated 1999 simulations prefer lower radiation conditions for maximum yields while crops experiencing little or no water stress prefer higher amounts. The precipitation simulations (see figs 11 and 12) also show the same general pattern, where once a certain point has been reached in terms of water amounts, the model no longer adds to the yield. The irregularity found in the 1999 Enhanced CO2 simulation in the altered species run is no longer present when the species parameters are restored (fig 12). Temperature patterns also show similar results (figs 13 and 14), where water stressed plants prefer cooler conditions. Again, the only difference aside from the yield amounts is that the irregularity found in the altered species 1999 Enhanced CO2 simulation is no longer present when using the restored species parameters and correct soil type.

Factor separation has some significant differences when the species file is restored. A marked difference exists in the manner in which 1999 Ambient simulations (both irrigated and non-irrigated) react to variable contributions and interactions (Figs 15 and 16). Where ambient conditions had negative contributions from ERP, ERT, and ERTP, these have switched sign and are now experiencing significant negative effects from these variable interactions. Specific interactions between these climate variables and amounts of CO2 in the atmosphere are evident once the species parameter has been restored. Increased CO2 levels may thus help crops deal with the potentially negative effects of these interactions. The rest of the variable contributions were similar to the altered species file simulation, except with markedly higher responses to increased radiation for the ambient irrigated conditions (fig 16).

Significant changes were also found in the 2000 simulations (fig 17 and 18). Where both enhanced and ambient CO2 conditions responded positively to ERT in fig 17, the opposite is the case in fig 18. This suggests season-specific responses to the radiation-temperature interaction (recall that individual parameter changes in figures 10 and 14 exhibited preferences for higher radiation and temperature). This could be due to the timing of the precipitation (overall amounts in 1999 and 2000 did not differ much) or specific patterns in temperatures throughout the season. The triple interaction (ERTP) also had positive contributions in the restored species file simulation (fig 18), compared to the markedly negative effects found in the altered species simulation (fig 17). Here, we believe that increases in the precipitation makes up for the negative effects of ERT, thus contributing to higher yields. Precipitation was also found to not be a factor in the newly performed runs (fig 18), which is in accordance to the findings in the individual precipitation change simulations (fig 12). ET was found to be negative in the enhanced 2000 run (fig 18), suggesting that the original species file is sensitive to higher temperatures regardless of CO2 amounts.

Overall, the changes we made in the species file have been reflected in our analysis by restoring more normal behavior to the 1999 enhanced CO2 simulations. The yields have been increased to more satisfactory levels and we have more confidence in the model's attempt to simulate chamber-grown plants. It is only in our factor separation analysis that we see some considerable differences between the two sets of runs in terms of crop sensitivity. Further work is necessary to analyze why this may be the case.

6.2.3 Temperature effects on 2000 season grain weight

We carefully analyzed the effects that a lower average temperature (-4°C) would have on the simulated 2000 season grain weight. For this we used seasonal temperature data (Figure 19) as well as growth analysis (Figure 20). We clearly recognize the hard freeze (<2°C) in early October. We also recognize that the plants started developing later than in the observed (Fig. 20) by more than a week and ends abruptly with the hard freeze.

6.3 Effects of seasonal climate patterns on grain weights for Chapter 3

In our study on the effects of future climate as predicted by an RCM (Chapter 3), we looked at interannual crop yield variability for our periods of study. We must note that although the amount of precipitation and average temperatures were similar in 2097 and 2099, season-specific factors may have played a hand in the discrepancies between the final yields (4977 kg/ha in 2097 and 820 kg/ha in 2099; both at 2099 CO2 levels). It is in the timing of the hottest temperatures (see Figs. 21 and 22) that the major differences in the yields are incurred. As portrayed in figure 23, the grain weight ceases to increase for the 2099 simulation in late September of that year but is always lower than that of 2097. There is an exceedingly warm period (higher than 35°C for several days) that occurs throughout the month of August in 2099. Conversely, in 2097 this happens in July. The major difference is that the warm period in 2099 occurs during the flowering of the crops, thus preventing flowering from occurring and causing low yields at the end of the year.

There are may be other factors involved in causing this low value, such as the timing of precipitation during certain growth stages or unfavorable patterns in solar radiation that was used as input. We must note that this is output from the model as given season-specific conditions as well as crop management practices. This could account for the lower values found in this particular experiment, but the evidence of the detrimental effects of warmer weather is still supported by the overall pattern found in Chapter 3.

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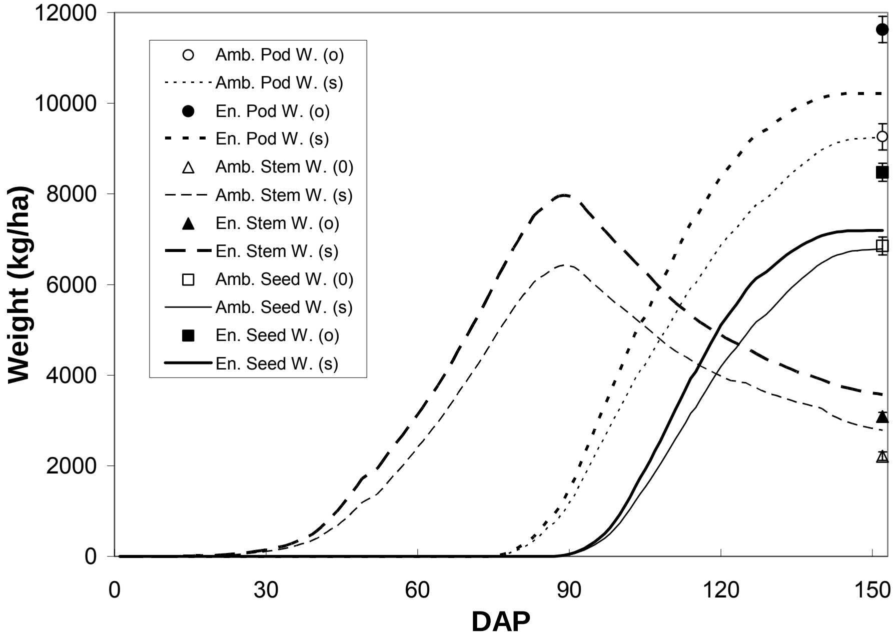

Figure 1. 1999 Original simulation with altered species file and Norfolk sandy clay loam.

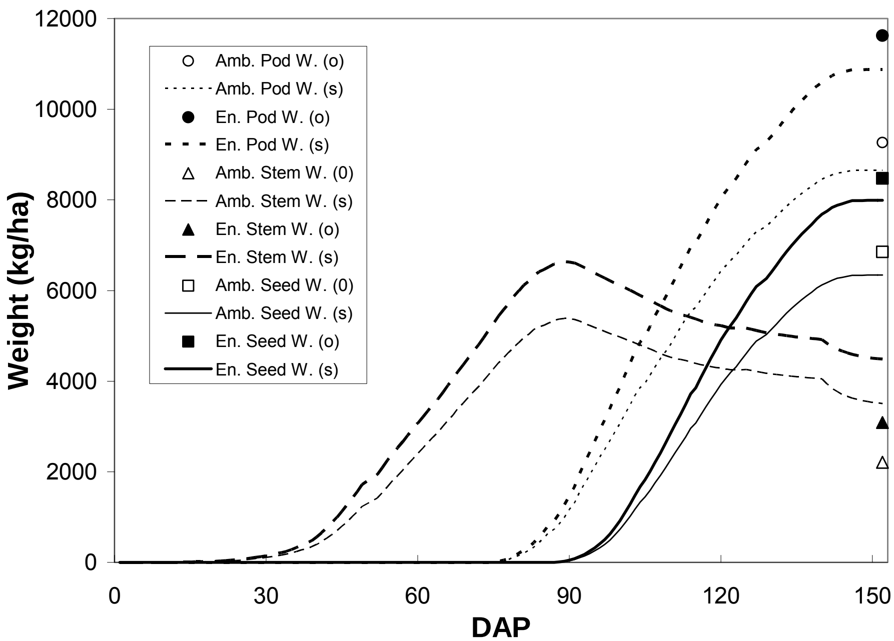

Figure 2. 1999 Simulation using original species file and Appling sandy loam

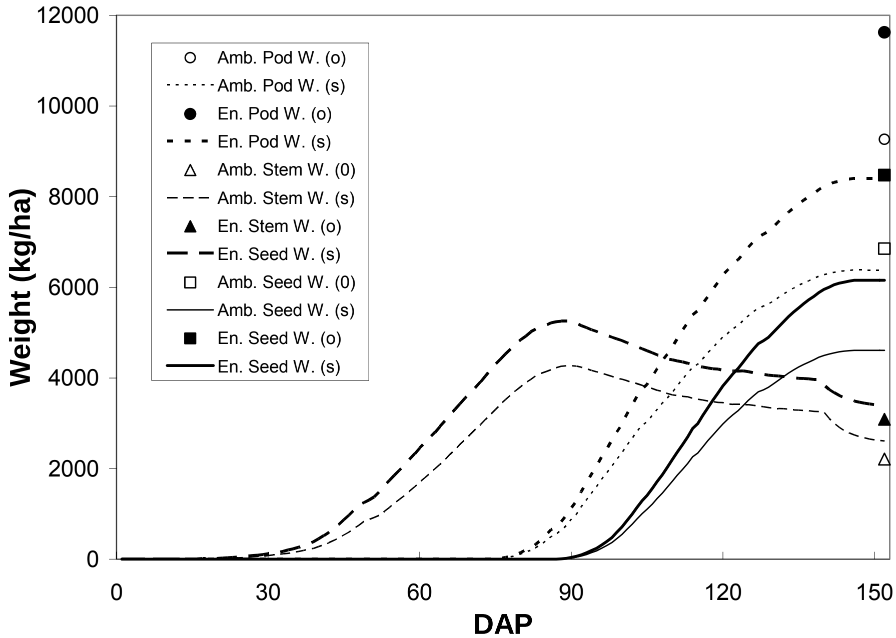

Figure 3. 1999 Simulation using Appling sandy loam with SLPF coefficient at 1.

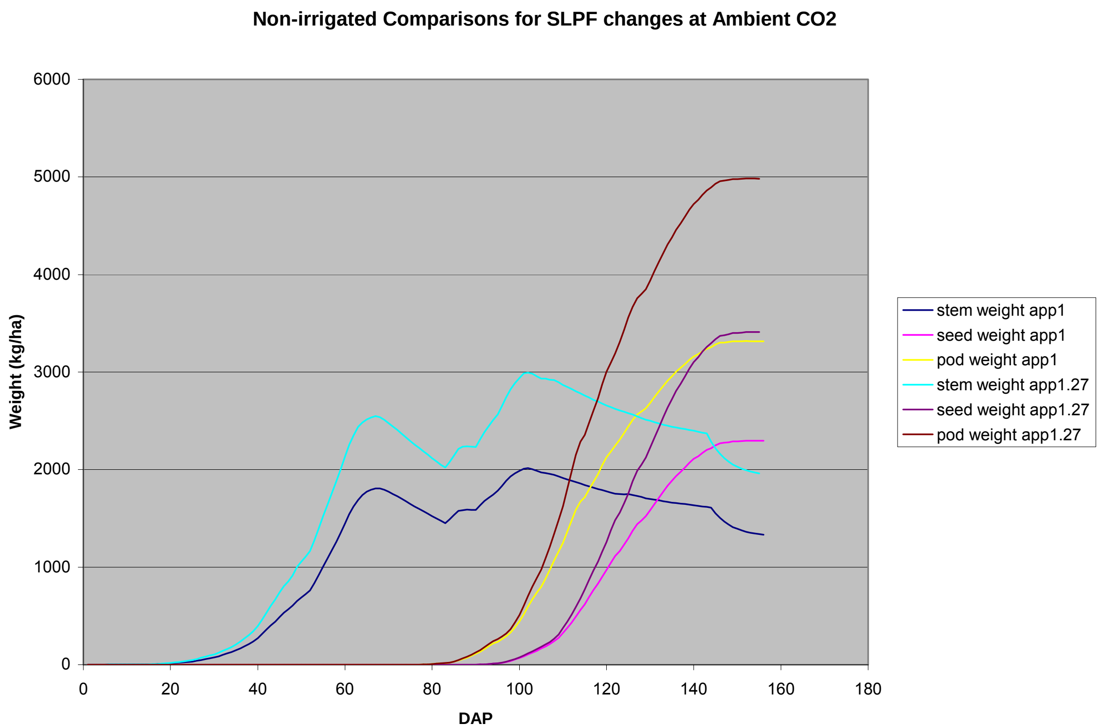

Figure 4. 1999 non-irrigated simulations.

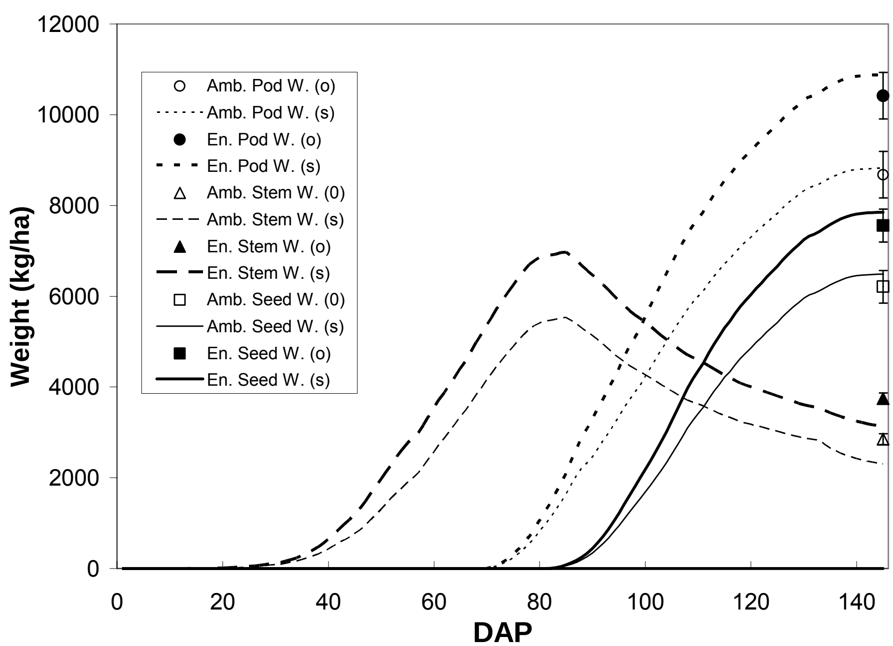

Figure 5. Same as fig 1 but for 2000.

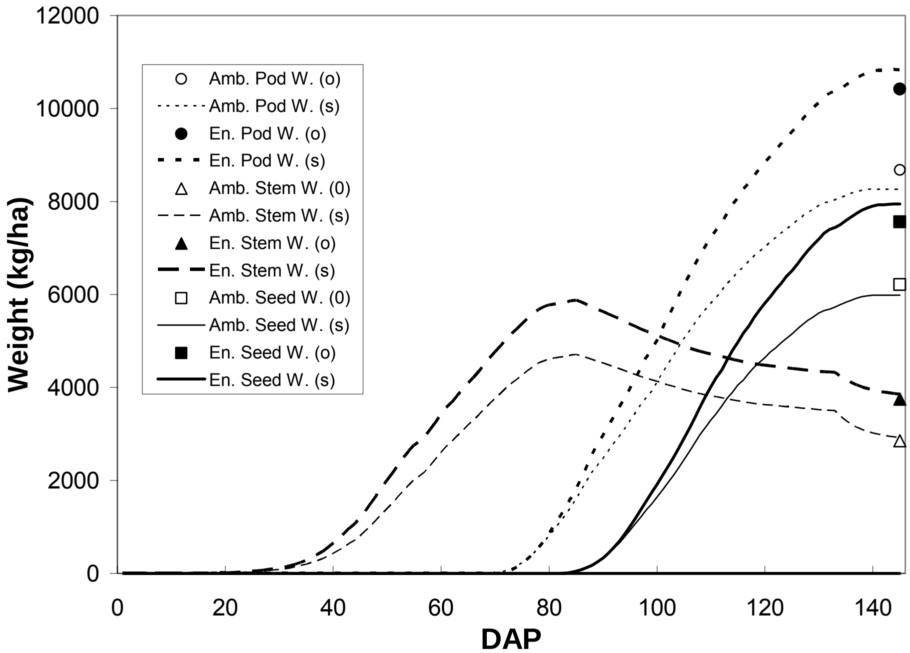

Figure 6. Same as Figure 2 but for 2000.

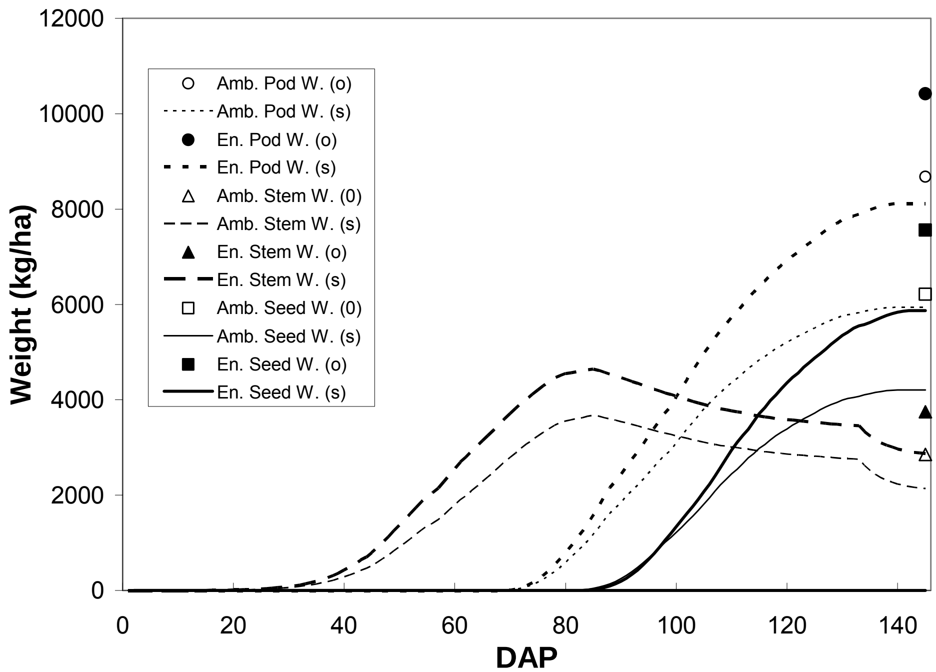

Figure 7. Same as Figure 3 but for 2000.

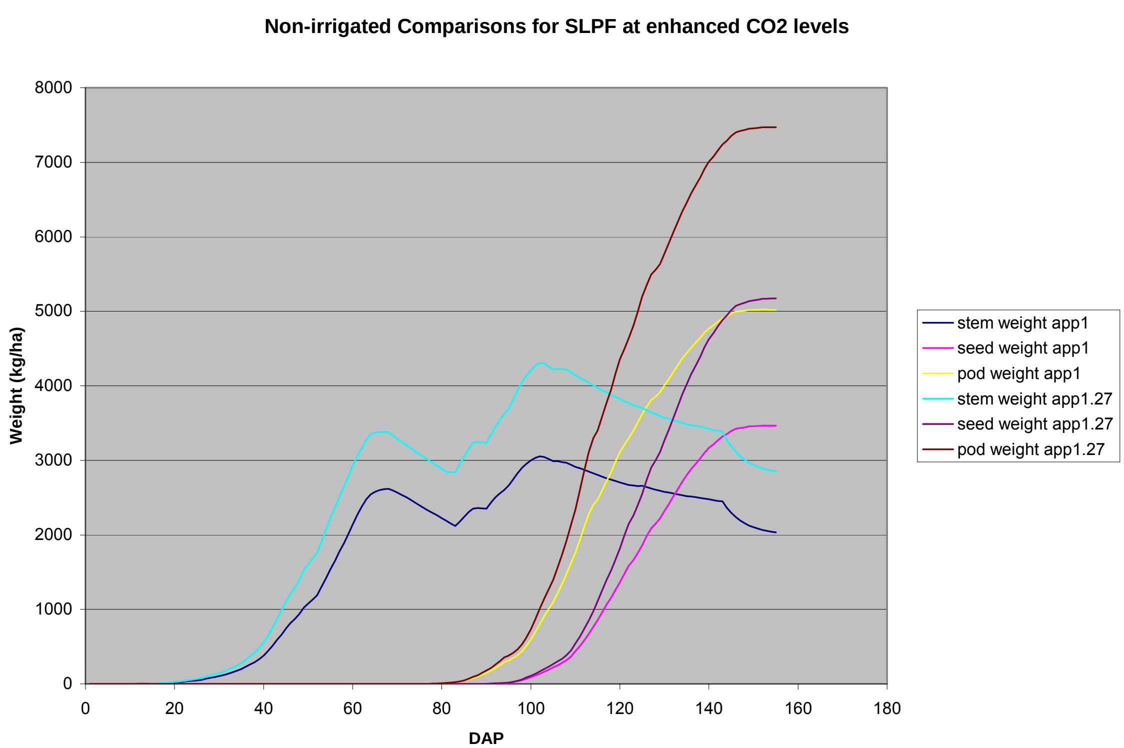

Figure 8. Same as Figure 4 but for 2000.

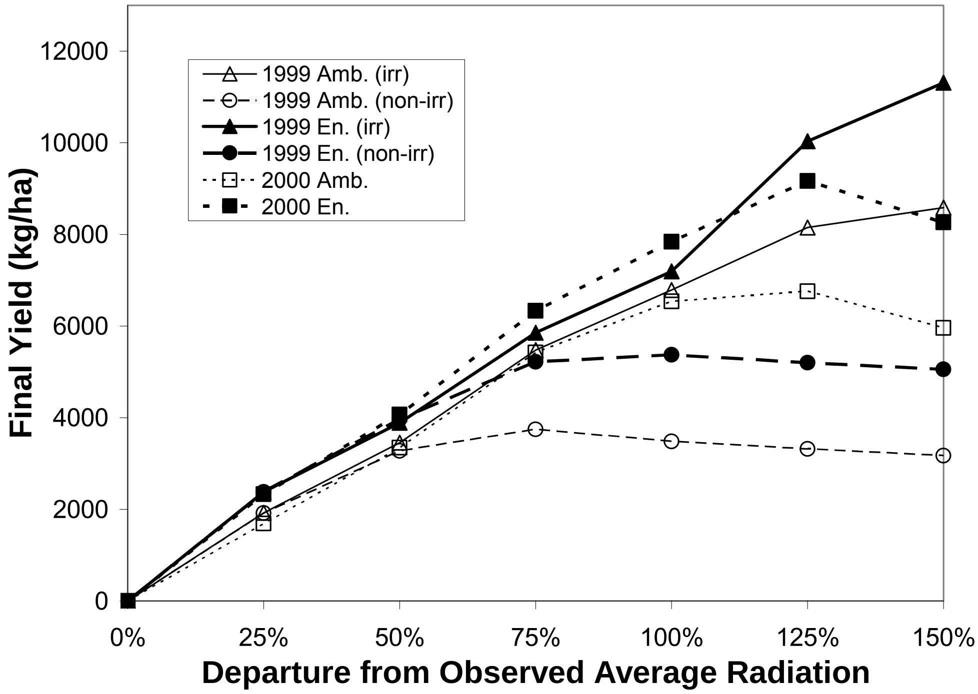

Figure 9. Radiation changes in altered species and Norfolk soil.

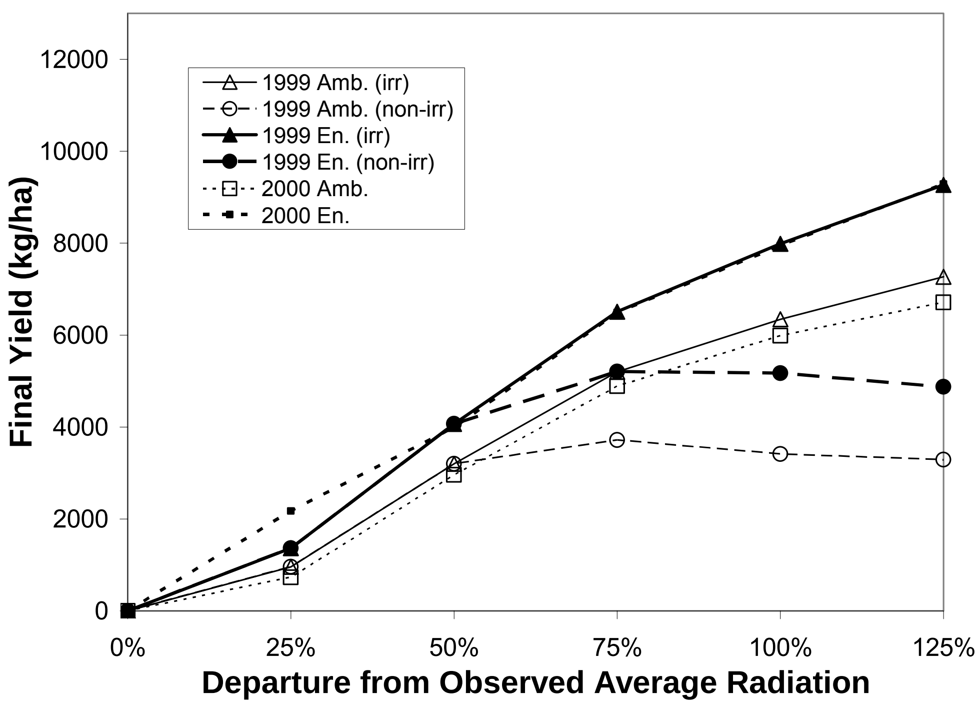

Figure 10. Same as Figure 9 but for original species and Appling soil (1.27 SLPF).

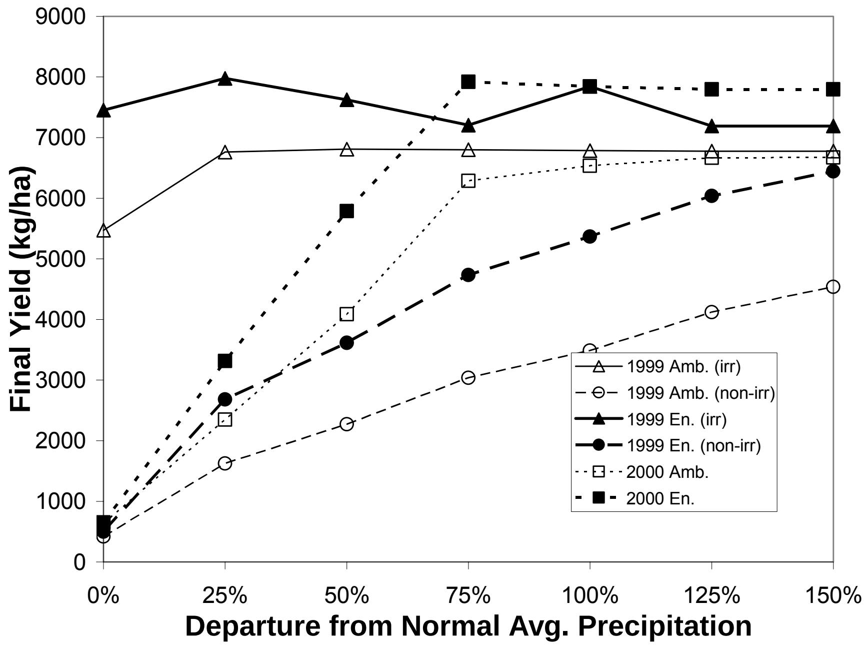

Figure 11. Precipitation change effects on crops in altered species and Norfolk soil.

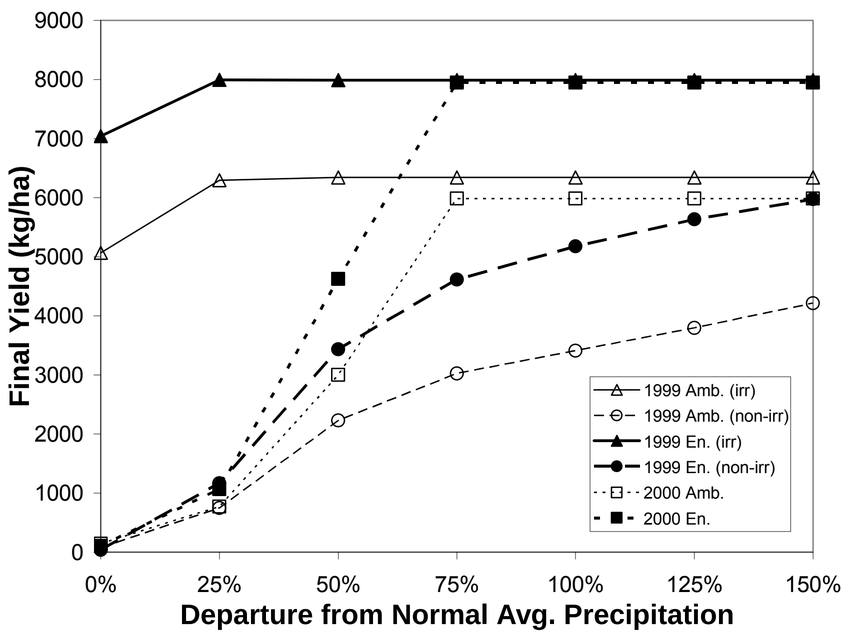

Figure 12. Same as Figure 11 but for original species and Appling soil (1.27 SLPF).

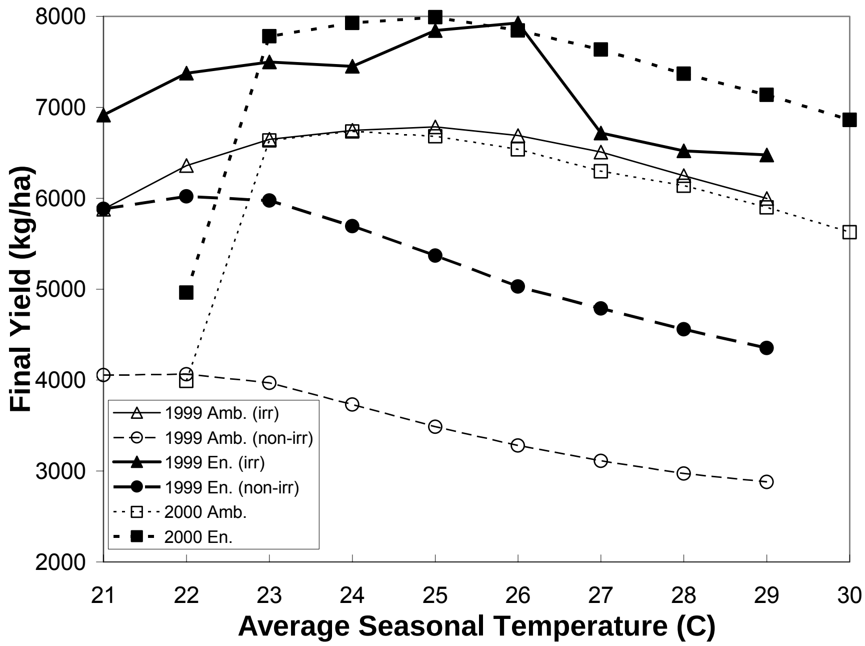

Figure 13. Temperature change effects on crop yields in altered species and Norfolk soil.

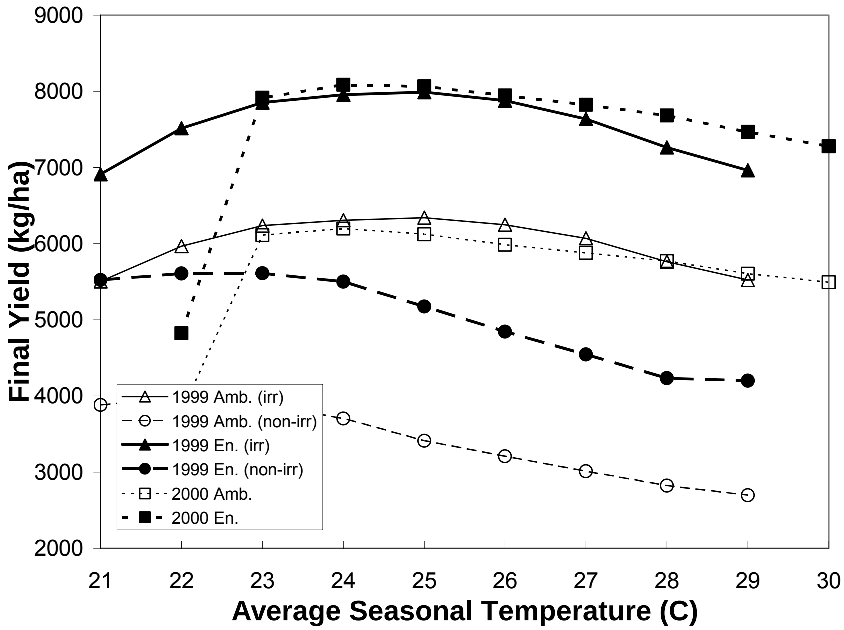

Figure 14. Same as Figure 13 but for original species and Appling soil (1.27 SLPF).

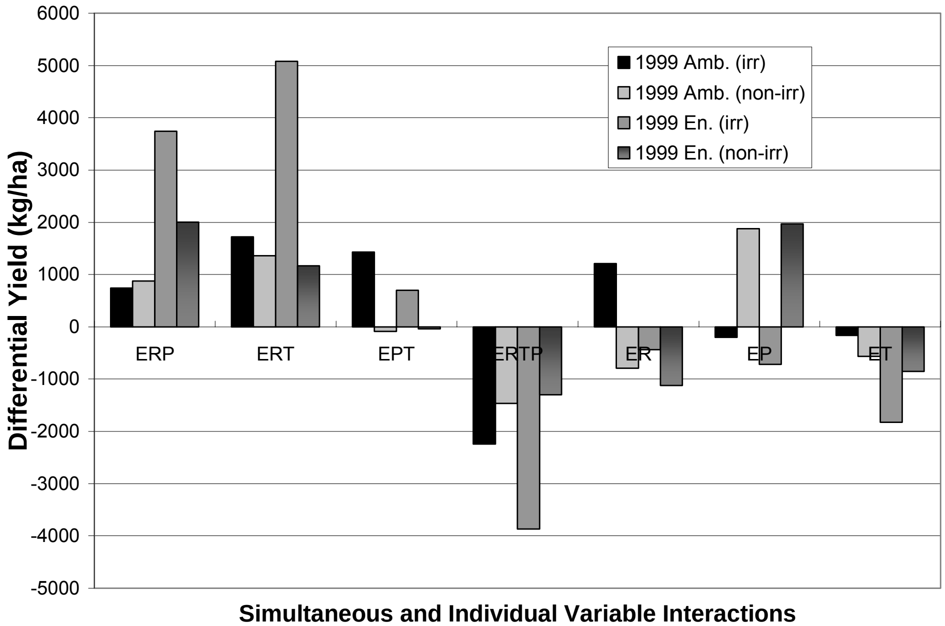

Figure 15. Factor Separation Plot for 1999 Soy Crop Differential Yield (kg/ha) at altered species and Norfolk soil.

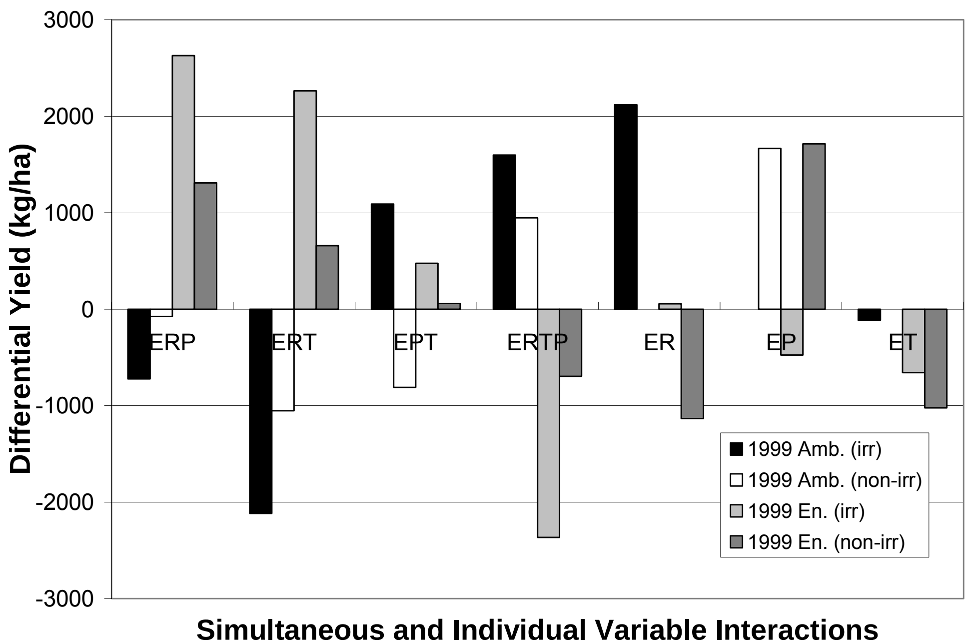

Figure 16. Same as Figure 15 but at original species and Appling soil (SPLF 1.27).

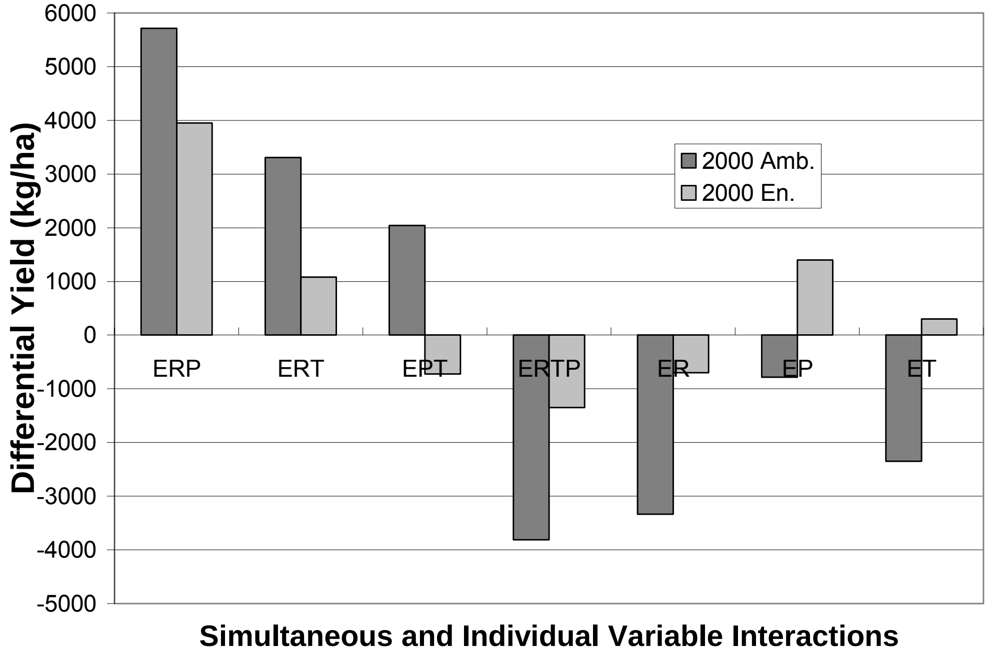

Figure 17. Same as Figure 15 but for 2000.

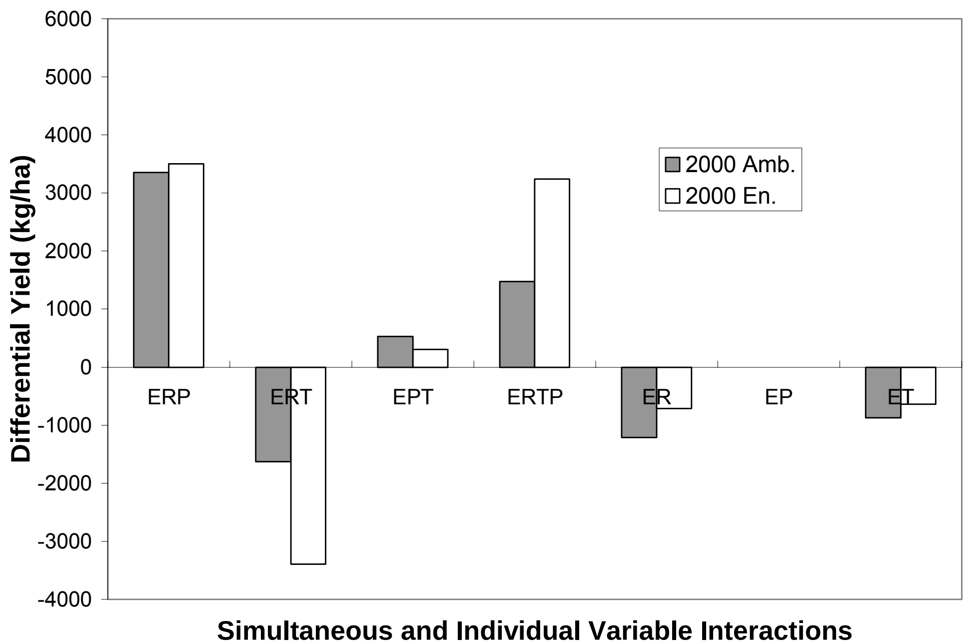

Figure 18. Same as figure 16 but for 2000.

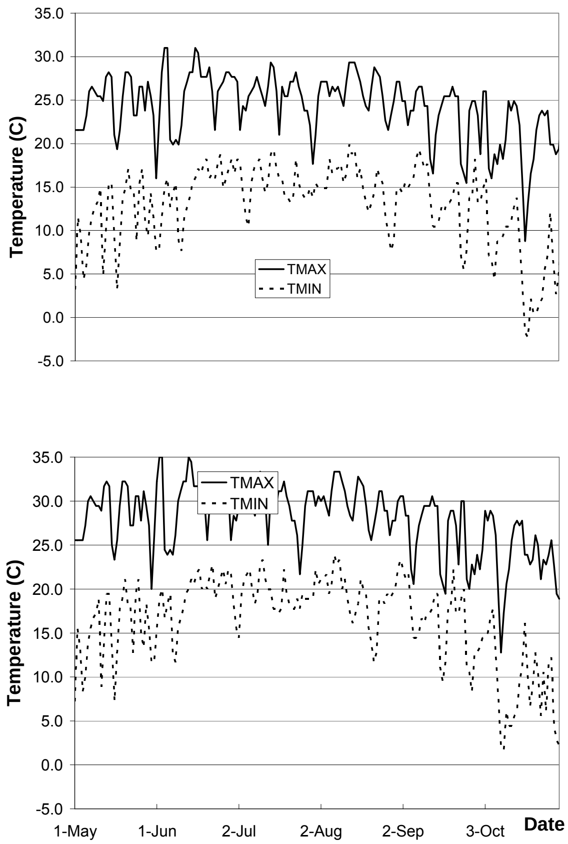

Figure 19. 2000 Season temperature data at -4 degrees of the average seasonal observed temperature (above) and observed (below).

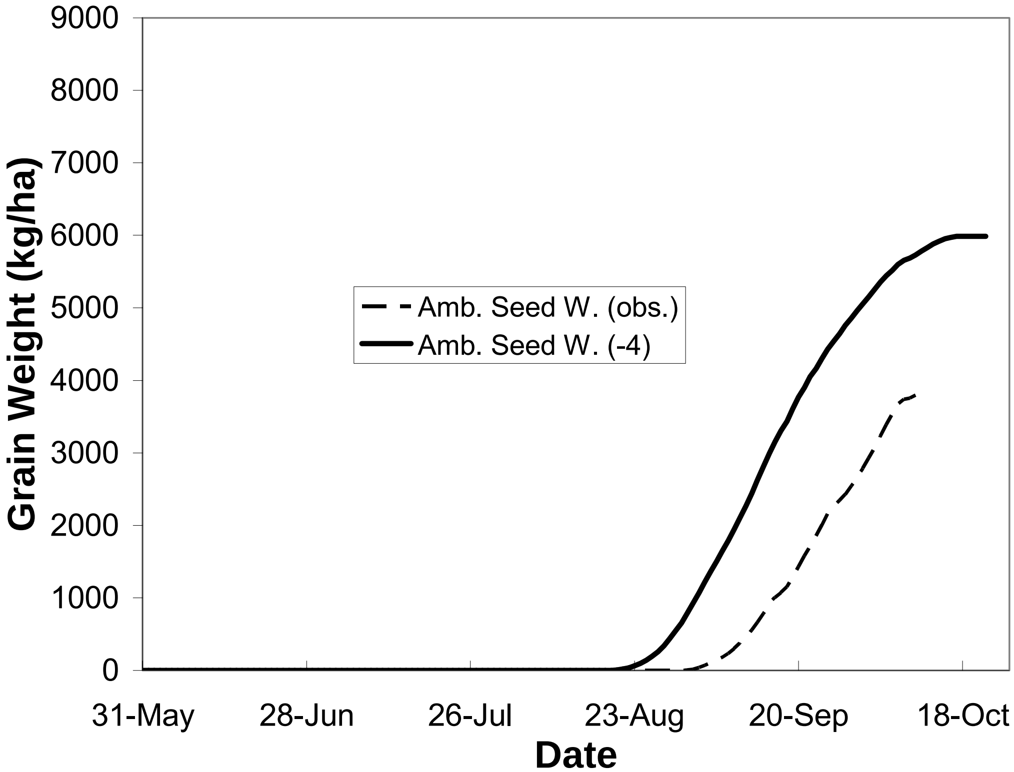

Figure 20. Growth analysis for 2000 season. Seed (grain) weight kg/ha is shown at observed average temperatures and altered (-4C) average temperatures.

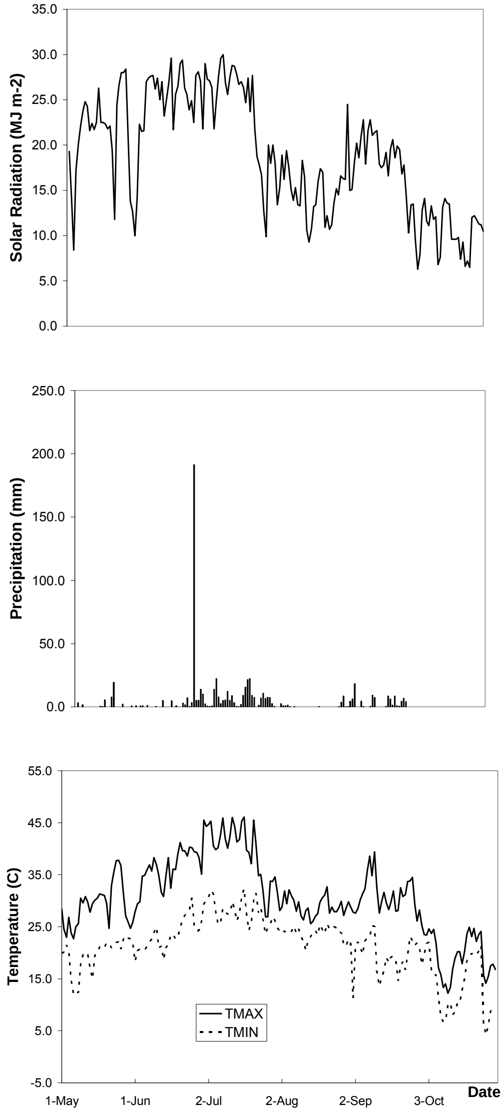

Figure 21. Daily climate for *A2* 2097 season in Chapter 3.

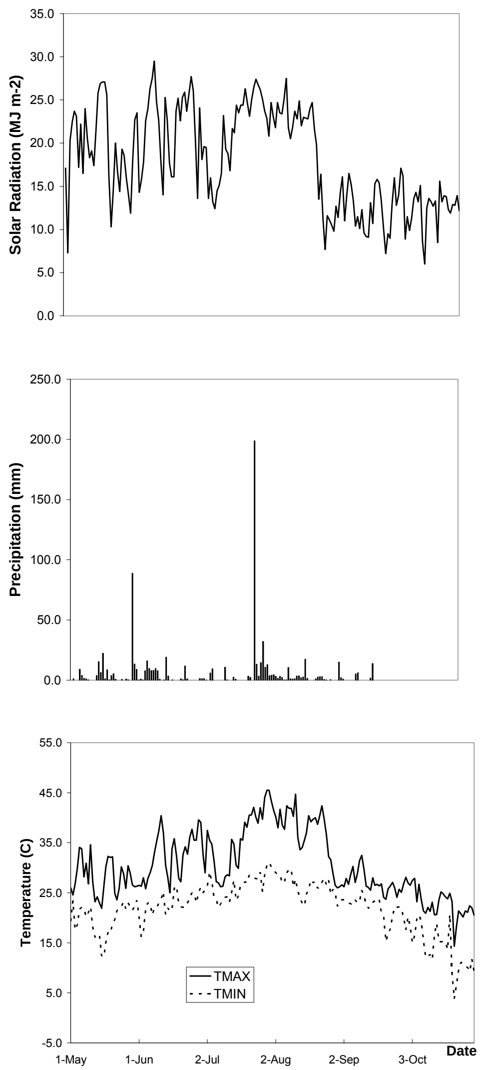

Figure 22. Same as Figure 21 but for 2099.

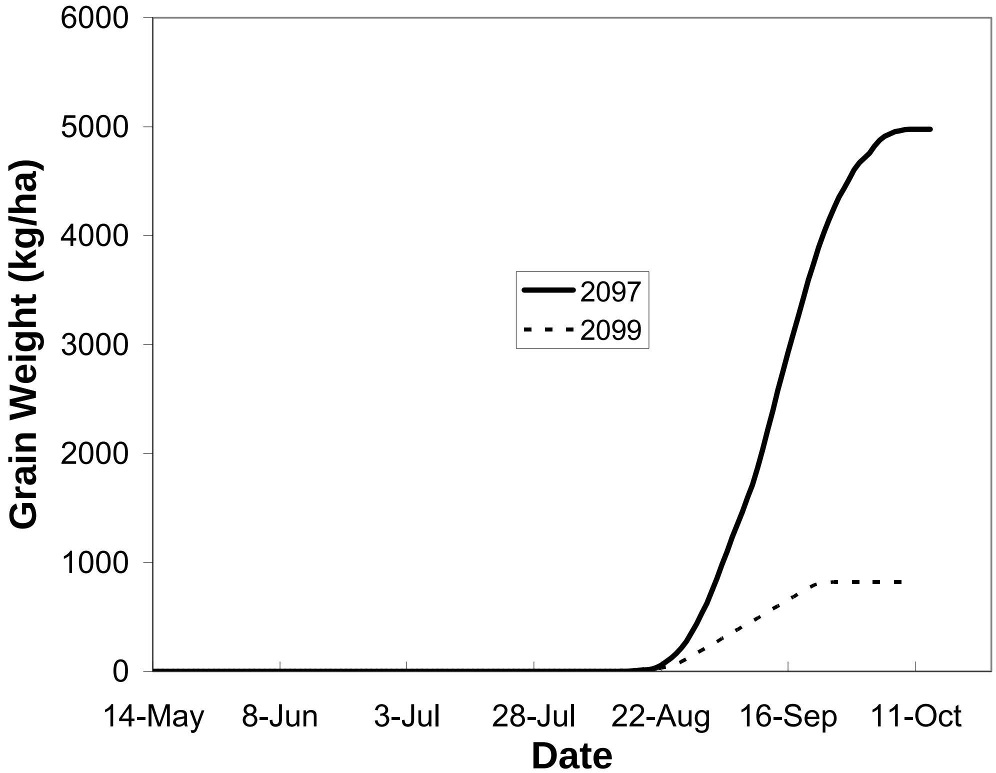

Figure 23. Growth analysis for grain weight during the 2097 and 2099 seasons for *A2* simulations in Chapter 3.