The Impact of Climate Variability on Wheat Growth and Yield

by

Mathew W. Tapley

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
August 4, 2012

Keywords: ENSO phase, planting date, relative maturity,
wheat, vernalization

Approved by

Brenda V. Ortiz, Chair, Assistant Professor of Agronomy and Soils
David Weaver, Professor of Agronomy and Soils
Paul Mask, Assistant Director Ag Foresty Natural Resources
Kipling Balkcom, Affiliate Associate Professor of Agronomy and Soils

Abstract

Understanding the environmental factors impacting wheat (*Triticum aestivum L.*) yield may lead to opportunities to increase yield potential. Variability in climatic conditions during the wheat growing season in the southeastern United States is strongly influenced by El Niño-Southern Oscillation (ENSO). Hence, ENSO forecast could potentially be used as a tool to adjust wheat management practices. Those adjustments focused on minimization of climate-related risks can be analyzed through the use of crop simulation models. To address this issue, this thesis studies the effect of planting date and variety selection on winter wheat production in Alabama. Additionally, evaluation of the Cropping System Model (CSM)-CERES-Wheat model was conducted for its ability to simulate growth, development, and grain yield of three different wheat varieties, as well as to determine yield response differences to planting date and variety selection combination based on ENSO phases.

The field study was conducted during 2009-2010 and 2010-2011 growing seasons at three research stations across Alabama: Tennessee Valley (TVREC), Wiregrass (WGS), and E. V. Smith (EVS). Wheat was planted in a randomized complete block design with split-plots and five replications. Four planting dates at approximately 15 day intervals were assigned to the main plots, and three varieties with early (AGS 2060), medium (AGS 2035), and late maturity (Baldwin) were randomized within subplots.

The simulation of wheat growth and yield was conducted using the Cropping System Model (CSM)-CERES-Wheat model, which was calibrated using data from three field studies. Data for the model evaluation was compiled from the 2008-2011 Alabama Performance Comparison of Small Grain Variety Trails. A seasonal analysis using 60 years of daily historic weather data was used to identify the impact of planting date and variety selection on yield as well as the wheat yield differences between ENSO phases.

Results showed yield differences associated with location by planting date, maturity group and year interactions. Regardless of location and year, yield decreased as planting was delayed for the medium and late maturing cultivar. This research showed that seed yield could be increased if the wheat cultivars were planted 15 days earlier than the standard planting date used by farmers at each location. The medium and late maturities varieties had the highest yield at all locations for the early planting dates. At the central location, EVS, there was little yield impact due to changes in planting dates and all three varieties tended to performed in a similar fashion. Overall results across locations suggested that yield can be increased via a higher seed weight instead of increasing the number of seed per spike. This can be achieved more easily with early plantings.

Results from simulation modeling showed that yield for all varieties decreased as planting was delayed at WGS and TVS. In contrast for EVS, the simulated average yield for the medium and late maturing varieties, AGS 2036 and Baldwin varieties, tended to be higher for later planting dates. During the La Niña years, the highest simulated wheat yield was observed compared to the other ENSO phases across all locations. The risk for yield losses associated with delayed planting was higher during El Niño phase than the

other ENSO phases, especially for the early maturing variety. In contrast, during La Niña and Neutral phases, AGS 2060, the early maturing cultivar, exhibited the lowest yield reduction associated with late planting compared to the AGS 2035 and Baldwin varieties. At EVS, there was not a clear trend for higher yield associated with the specific variety to ENSO phase. At WGS, the early maturing variety, AGS2060, exhibited the highest yield reduction (16.9%), followed by AGS 2035 (16.25%) and Baldwin (12.8%) during the El Niño years when planting date 1 was compared to the latest planting date. During La Niña years, yield reductions when comparing the first planting date to the last planting date were smaller than for the El Niño years with differences between varieties of 10.45% for AGS 2060 followed by Baldwin with 11.89%, and AGS 2035 with 12.32%. Neutral years exhibited a broad range of yield reduction differences between locations and varieties. For TVS, AGS2060 had the lowest yield reduction (18.89%) followed by Baldwin (24.17%) and AGS 2035 (25.44%) for same planting dates comparisons. Further studies should focus on the evaluation and application of the CSM-CERES-Wheat model for other management practices and other agroclimatic regions where wheat is an important crop.

Acknowledgments

The author would like to express his gratitude to his major professor, Brenda V. Ortiz, for her support and guidance throughout the study. He would also like to express his appreciation to the members of his committee: Dr. David Weaver, Dr. Paul Mask, and Dr. Kipling Balkcom for their valued knowledge and direction. The author would also like to thank Dr. Edzard van Santen, Dr. Gerrit Hoogenboom, Hunter Stone, Kathy Glass and the student workers for their valued advice and aid in the field, which was essential in the completion of the research conducted. He would also like to acknowledge the personal at the E.V. Smith Research Unit, Wiregrass Research Unit, and Tennessee Valley Research Unit for their assistance. The author would like to extend his appreciation to the Agronomy and Soils Department of Auburn University for the opportunity to continue his education and the assistance provided. Also, he would like to extend his deepest gratitude to his family and friends for the support throughout this endeavor.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AL	Alabama
AU	Auburn University
AWIS	Agricultural Weather Information Service
C	Celsius
cm	Centimeter
CN	Curve Number
CSM	Crop Simulation Model
COAPS	Center of Ocean-Atmospheric Prediction Studies
COOPS	Cooperative Observer Program
DAP	Days after Planting
DUL	Drained Upper Limit
DSSAT	Decision Support System for Agrotechnology
ENSO	El Nino-Southern Oscillation
EVS	E. V. Smith Research and Extension Center
h	Hours
ha	Hectare
HI	Harvest Index
IU	International Unit

JMA	Japan Meteorological Agency
kg	Kilogram
LAI	Leaf Area Index
LL	Drained Lower Limit
m	Meter
mm	Millimeter
MJ	Mega Joules
NRCS	Natural Resource Conservation Service
PD	Planting Date
RMSE	Root Mean Squared Error
SAT	Saturated Upper Limit
SECC	Southeast Climate Consortium
SLPF	Soil Fertility Factor
SRAD	Solar Radiation
TMAX	Temperature Maximum
TMIN	Temperature Minimum
TVS	Tennessee Valley Research and Extension Center
USDA	United States Department of Agriculture
WGS	Wiregrass Research and Extension Center

I. Literature Review

Planting Date and Cultivar Selection for Winter Wheat Production

Over the last few decades, climate change and climate variability has been the center of many scientific studies (Hulme et al., 1999). These changes and variations in climate are explained by natural processes as well as anthropogenic factors and can be seen throughout large and small periods of time. In both developed and developing countries, the agricultural system still remains dependant on climate related resources (Downing, 1996; Watson et al., 1996). This dependence on climatic conditions tends to have some effects on the economics of not only the specific location but in some cases at the regional and even worldwide scale (Kaufmann and Snell, 1997; Freckleton et al., 1999; Gadgil et al., 1999).

Soft red wheat (*Triticum aestivum L.*) is a winter crop often planted in the southeastern United States for use as a cover and/or forage crop or harvested for grain. It has recently gained more attention due to its potential as a low cost ethanol feedstock (Beres et al., 2010; Palmarola-Adrados et. al., 2005). This increased interest along with worldwide wheat demand represented on 190 million tons of net wheat imports by the year 2050 (FAO, 2006), suggest that wheat farmers might have to modify management practices in order to optimize and increase yield.

Planting date of wheat has been identified as a major factor impacting productivity (Cambell et al., 1991; McLeod et al., 1992; Sun et al., 2007). Changes in planting date result in differences in vernalization, and accumulation of heat units and precipitation by the plant throughout the growing season. These factors have been shown to influence wheat yield potential by affecting the number of seed per unit area and weight per seed, factors that determine grain yield (Fisher, 1975; 1985; Sun et al., 2007). When winter wheat is planted early, the plant is exposed to longer periods of beneficial climatic and soil conditions, such as adequate soil moisture and increased temperatures that are favorable for germination (Blue et al., 1990), which result in deeper root growth and favorable vegetative growth before colder weather arrives and decreases the growth rate. The increase in root and vegetative growth has many benefits including a well established crop cover of bare soil which result in less erosion and runoff, and higher water infiltration (Incerti and O’Leary, 1990; Winter and Musick, 1993). The down side of early fall planting dates is the increased risk for diseases such as wheat streak mosaic, high plains virus, barley yellow dwarf, sharp eyespot, common root rot, and take-all root rot as well as pests like hessian fly (Blue et al., 1990; Epplin et al., 1999). Studies conducted in Denmark indicate that earlier planting dates extend the growing season allowing total precipitation to increase which has a positive correlation with dry land wheat yield (Olesen et al., 2000). According to Olesen et al., (2000) benefits of an extended growing season are even more evident when wheat is planted in sandy soils due to low water holding capacity. The influence of precipitation, amount and distribution, during the spring months seems to correlate also with higher yields on wheat was reported by Rasmussen et al. (1998). Contrary to the benefits of early plantings, delayed planting could cause yield losses (Chen et al., 2002). Late planting dates have a tendency to experience more temperature fluctuations, which could shorten grain filling (Sofield et al., 1977; Wardlaw et al., 1980; Al-Khatib and Paulson, 1984; Hunt et al., 1991; Jenner, 1991; Slafer and Rawson, 1994), affect the duration of spike growth, increase spike sterility (Wheeler et al., 1996), and delay maturity if temperatures increase during pre- and post- anthesis growth stages.

In Alabama, recommended planting dates for wheat are region specific. The ranges of planting dates for grain production are as follows: Northern, AL - 15 Oct. to 1 Nov., Central, AL – 15 Oct. to 15 Nov. and Southern, AL – 1 Nov. to 1 Dec (Flanders et al., 2012). For specific cultivars with early maturating dates, the planting dates are as follows: 15 Nov. to 15 Dec. (Flanders et al., 2012).

Wheat cultivars have a broad range of vernalization requirements, some needing little to no cold treatment, such as spring wheat cultivars, while others have long requirements, such as hard red winter wheat cultivars. When a specific cultivar does not accumulate the amount of chill hours, flowering will not occur (Ahrens and Loomis, 1963; Chujo, 1966). Changes in planting date might be beneficial or detrimental for vernalization requirements (Levitt, 1948; Aitken, 1961; Tottman, 1977). The effect of limited vernalization on wheat could affect the timing of floral initiation, number of leaves, timing of the emergence of the leaf flag, and number of total tillers (Griffiths et al., 1985; Brooking, 1996. Gott et al., 1955), which will impact vegetative growth (Levy and Peterson, 1972). Correctly matching wheat’s phenology to the dominant environment would result in maximization of the adaptation and crop yield (Gomez-Macpherson and Richards, 1995). Therefore, farmers have to choose an appropriate planting date for a specific cultivar which will flower at the optimum time, hence reducing climate-related risks and increasing yield.

Low temperatures are needed to achieve the necessary vernalization requirements, but if the temperature falls below 20°C, there has been observed decreases in the length of stem elongation (Slafer and Rawson, 1994). If the low temperature persists into the anthesis stage, the number of infertile florets can increase (Chugo,1966).

Vernalization requirements could be impacted by seasonal and inter-annual climate variability associated with the El Niño Southern Oscillation (ENSO). In the Southeast US during the El Niño phase of ENSO, warming of the equatorial Pacific's sub-surface ocean temperatures, lower than average ambient temperatures and above average precipitation are prevalent during winter and spring months. The contrary, La Niña phase, cooling of the equatorial Pacific's sub-surface ocean temperatures, result in increased temperature and precipitation below average values. These climatic variations associated with ENSO could then impact wheat growth and yield. Therefore, a better understanding of the effect planting date and cultivar maturity on wheat yield in the Southeast is needed in order to modify management practices to reduce climate related risks. The objective of this study was to determine the effect of planting date and cultivar selection on grain yield and yield components of winter wheat growing under the environmental conditions of three locations in Alabama.

Crop Simulation Modeling

Variations in temperatures have been observed in the Equatorial Pacific Ocean's sub-surface temperatures, a warming trend (El Niño), a cooling trend (La Niña), and a trend of normal temperature (Neutral) have been given the name Southern Oscillation. This phenomenon is commonly known as El Niño Southern Oscillation (ENSO) phase. Several studies have linked this event to global changes in temperature and precipitation using different approaches and climate data sets (Douglas and Englehart, 1981; McBride and Nicholls, 1983; Ropeleski and Halpert, 1986, 1987, 1996; Sittel, 1994; Green, 1996). ENSO phase is classified by the Japan Meteorological Agency (JMA), which classifies based on six main observed variables: sea-level pressure zonal and meridional components of the surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky. This data is compiled and a prediction is made for the specific time period. El Niño, the warm phase of ENSO, is described as a warming of the equatorial Pacific Ocean surface temperatures. In the Southeast, this ENSO phase has been associated with lower temperature and higher precipitation and is related to a reduction in solar radiation (Hansen et al., 1998). In contrast, a cooling on the equatorial Pacific Ocean sea surface temperature described as La Niña phase of ENSO is related to an increase in temperature and decrease in precipitation in the Southeast United States. The impact of ENSO phases on weather patterns is evident in the fall and spring seasons and strongest during the winter season (Ropelewski and Halpert, 1986; Kiladis and Diaz, 1989; Hanson and Maul, 1991; Sittel, 1994). Due to the importance of soil moisture and vernalization requirements in wheat, seasonal and interannual climatic variations associated with ENSO could impact wheat production.

In the Southeast United States, production, price fluctuations, and ability to harvest row crops such as corn (*Zea mays* L.), soybean (*Glycine max* L.), peanut (*Arachis hypogaea* L.), cotton (*Gossypium hirsutum* L.) and wheat (*Triticum aestivum* L.); as well as yield reductions for several horticultural and row crops including bell peppers (*Capsicum annum* L.), and tomatoes (*Solanum lycopersicum* L.) have been associated with ENSO phases (Hansen et al., 1998; Hansen et al., 2001). In Australia, South Asia, and mid-North America, ENSO has been found to have an adverse impact on cereal production which includes risks for diseases like wheat rusts (Garnett and Khandekar, 1992; Scherm and Yang, 1995) and yield losses (Nicholls, 1985; Nicholls, 1992; Hayman et al., 2010).

Forecast for ENSO can be used to help decide which management practices and other agricultural decisions could optimize yield and yield components (Hildebrand et al., 1999). Climate forecast has been shown to benefit agricultural systems by changing management practices such as planting dates (Soler et al., 2007), nitrogen application (Asseng et al., 2011), fungicide application (Hildebrand et al., 1999) and others for minimizing the adverse impacts or maximizing the beneficial impact on crop yield. Cusack (1983) and Sah (1987) suggested that the use of climate forecasting could lead to the next ‘Green Revolution’. Adams et al. (1995) estimated the annual economic benefits of ENSO-driven climate forecasting for southeast agricultural systems to be $100 million.

Crop simulation modeling can be used as a research tool for the analysis of varying specific management practices for a specific location. These management practices include but are not limited to: fertilizer application, planting density, planting date, and variety selection (Tsuji et al., 1998; Ruiz-Nogueira et al., 2001**;** Saseendran et al., 2005**).**

Identification of changes on management practices through field experimentation might take several years of data collection before reaching definite conclusions. In recent years, crop models have been used for the support of agronomic research, field agronomic advice, and decision support for agricultural policy formulation (Boote et. al., 1996).

Crop modeling along with short term field experiments could be used to improve agronomic management and/or quantify yield losses associated with biotic stress, as well as tools for the evaluation of alternative management practices for a particular location over a broad range of seasons and also to assess long-term climate risks on crop yield. The analysis of crop simulation results allows the researcher to focus on the yield reducing factors and provide better recommendations to producers.

Decision Support System for Agrotechnology Transfer DSSSAT 9.0 (Hoogenboom et al., 2010; Jones et al., 2003) which includes the Cropping System Model (CSM)-CERES-Wheat model is a comprehensive decision support system for assessing management options. The CSM-CERES-Wheat model, operating on a daily time step from planting to maturity, allows simulation of growth, development and yield under a variety of weather, soil conditions, management practices and environmental conditions throughout the world (Bannayan et al., 2003; Nain et al., 2004; Barbieri et al., 2008; Langensiepen et al., 2008; Xiong et al., 2008; Persson et al., 2010; Soler et. al., 2007). Crop growth models, for the southeast U.S., have been previously applied to the evaluation of several management practices for several cropping systems; the CSM-

CERES-Wheat model was used to evaluate potential of wheat grain and straw as an alternative to fossil fuels as an energy source for Alabama and Georgia (Persson et al., 2010). Garcia y Garcia et al. (2008) evaluated the impact of generated weather variables on rainfed and irrigated cotton, maize and peanut through the use of the CSM-CROPGRO-Cotton, CSM-CERES-Maize, CSM-CROGRO-Peanut models for several counties in Georgia. The CSM-CROPGRO-Cotton model has been used to evaluate the effects of shading on cotton when planted in a pecan alley system in southern Georgia (Zamora et al., 2009). The CROGRO-Peanut model has been used to evaluate irrigation practices for peanuts grown in Georgia (Paz et al., 2007).

The weather data that is needed for the CERES-Wheat model is the daily maximum and minimum mean temperatures, solar radiation, and precipitation. These numerical values are used to predict the climate that is present in the area being modeled. Weather data has been used in simulation modeling for the prediction of several growth variables, insect pest, and disease in specific crops (Jabrzemski and Sutherland, 2004). Daily maximum and minimum mean temperatures, solar radiation, and precipitation for three locations were compiled for the purpose of the calibration and further analysis on the effect of each specific ENSO phase. This minimum data set was obtained from the Cooperative Observer Program (COOP) network and compiled by the Center for Ocean-Atmospheric Prediction Studies (COAPS), through the aid of the Southeast Climate Consortium (SECC).

Crop phenology, growth, and yield, in the CERES-Wheat model, is predicted through the specific cultivar genetic coefficients depending on photoperiod, thermal time, temperature response and dry matter partitioning (Alexandrov and Hoogenboom, 2000).

The amount of light interception is used to predict the leaf growth, development and expansion (Alexandrov and Hoogenboom, 2000). This is because the light interception is assumed to be proportional to the biomass production. The CERES model predicts biomass partitioned into groups, such as leaves, stems, and heads. Through the modeling simulation, it uses the management practices to simulate and determine the best scenario for agronomic crop growth.

The soil water balance submodel used in CERES-Wheat found in the DSSAT program is described in detail by Ritchie (1998).The volumetric soil water content varies among each soil layer between a lower limit (LL- corresponding to the permanent wilting point) and a saturated upper limit (SAT- corresponding to the saturation point). If the water content is above the drained upper limit (DUL- corresponding to field capacity), then the water drains to the next soil layer. Soil infiltration and runoff of rainfall is dependent on the U.S. Soil Conservation Service runoff curve number (CN2). This was based on the specific soil characteristic. The runoff curve number was used to estimate potential evapotranspiration, the model uses the method of Priestley and Taylor (1972). Potential plant transpiration will be calculated through an asymptotic function of leaf area index and potential evapotranspitation.

The objectives of this study was to (i) to evaluate the performance of the CSM-CERES-Wheat model for simulating growth, development and yield for three winter wheat varieties of different maturity growing at three different locations in Alabama and (ii) to analyze the effect of ENSO phase on yield of three wheat varieties planted at four different times for three locations in Alabama using the CSM-CERES-Wheat model.

References

Adams R.M., K.J. Bryant, B.A. McCarl, D.M. Legler, J. O’Brien, A. Solow, R. Weiher. 1995. The value of improved long range weather information. Contemp Econ Policy 13:10–19.

Ahrens J.F., and W.E. Loomis. 1963. Floral induction and development in winter wheat. Crop Sci. 3: 463-466.

Aitken Y. 1961. Flower initiation in relation to maturity in crop plants. I. Internode lengthening in relation to grazing oat varieties. Australian J. of Agri. Res. 12: 389-396.

Al-Khatib K., and Paulsen G.M., 1984. Mode of high temperature injury to wheat during grain development. *Physiologia Plantarum* 61:363-368.

Alexandrov, V.A., G. Hoogenboom. 2000. The impact of climate variability and change on crop yield in Bulgaria. Agric. and Forest Meteorol.104:315-327.

Asseng, S., P.C. McIntosh, G. Wang, and N. Khimashia. 2011. Optimal N fertilizer management based on a seasonal forecast. European J. Agron. 38:66-73.

Bannayan, M., N.M.J. Crout, and G. Hoogenboom. 2003. Application of the Ceres-Wheat model for within season prediction of winter wheat in the United Kingdom. Agron. J.95:114-125.

Barbieri, P., H.S. Rozas and H.E. Echeverria. 2008. Time of nitrogen application affects nitrogen use efficiency of wheat in the humid pampas of Argentina. Can. J. of Plant Sci. 88:849-857.

Beres, B.L., K.N. Harker, G.W. Clayton, E. Bremer, R.E. Blackshaw, and R.J. Graf. 2010. Weed-Competitive Ability of Spring and Winter Cereals in the Northern Great Plains. Weed Technol. 24: 108-116.

Blue, E.N., S.C. Mason, and D.H. Sander. 1990. Influence of planting date, seeding rate, and phosphorus rate on wheat yield. Agron. J. 82: 762-768.

Brooking, I.R. 1996. Temperature Response of Vernalization in Wheat: A Developmental Analysis. Ann. of Bot. 78: 507-512.

Boote, K.J., J.W. Jones, and N.B. Pickering. 1996. Potential uses and limitations of crop models. Agron. J 88:704-716.

Cambell, C.A., F. Sellers, R.P. Zentner, J.G. McLoed, F.B. Dyck. 1991. Effects of seeding date, rate anddepth of winter wheat grown on conventional fallow in Southwestern Saskatchewan. Can. J. of Plant Sci. 71:51-61.

Chen, C., W.A. Payne, R.W. Smiley, M.A. Stoltz. 2002. Yield and water-use efficiency of eight wheat cultivars planted on seven date in northeastern Organ. Agron. J. 95:836843.

Chouard, P. 1960. Vernalization and its relations to dormancy. Ann.Rev. of Plant Physiol. 11: 191-237.

Chujo H. 1966. Difference in vernalization effect in wheat under various temperatures. J. of the Crop Sci. Soc. of Japan 35: 177-186.

Cusack, D.F. 1983. Introduction: reviving the Green Revolution. In: Cusack, D.F. (Ed.). Agroclimate Information for Development: Reviving the Green Revolution. Westview Press. Boulder, CO, USA. pp. xii-xvi.

Douglas, A. V. and Englehart, P.: 1981, ‘On a Statistical Relationship between Autumn Rainfall in the Central Equatorial Pacific and Subsequent Winter Precipitation in Florida’, *Mon. Wea. Rev.* 109, 2377–2382.

Downing, T.E. (Ed.), 1996. Climate change and world foodsecurity. NATO ASI Series. Series I: Global Environmental Change 37, Springer, Berlin, 662 pp.

Epplin, F.M., I. Hossain, and E.G. Krenzer Jr. 1999. Winter wheat fall-winter forage yield and grain yield response to planting date in a dual-purpose system. Agricultural Systems 63: 161-173.

FAO. 2006. World agriculture: towards 2030/2050. Food and Agriculture Organization of the United Nations. http://www.fao.org/fileadmin/user_upload/esag/docs/Interim_report_AT2050web.pdf (accessed 05 Jun. 2012)

Fisher, R.A. 1975. Yield potential in dwarf wheat and the effect of shading. Crop Sci. 15: 607-613.

Fisher, R.A. 1985. Number of Kernels in wheat crops and the influence of solar radiation and temperature. J. of Agric. Sci., Cambridge 105: 447-446.

Flanders, K. L., A. K. Hagan, M. G. Patterson B. V. Ortiz. 2012. Small Grains: Insect, Disease, and Weed Control Recommendations for 2012. Alabama Cooperative Extension System.

Fox, G., Turner, J., T. Gillespie. 1999. The value of precipitation forecast information in winter wheat production. Agric. and Forest Meteorol. 95: 99-111.

Freckleton, R.P., Watkinson, A.R., Webb, D.J., Thomas, T.H., 1999. Yield of sugar beet in relation to weather and nutrients. Agric. For. Meteorol. 93 (1), 39–51.

Gadgil, S., Rao, P.R.S., Sridhar, S., 1999. Modeling impact of climate variability on rainfed groundnut. Curr. Sci. 76 (4), 557– 569.

Garcia Y Garcia, A., L.C. Guerra and G. Hoogenboom. 2008. Impact of generated solar radiation on simulated crop growth and yield. Ecological Modeling 210:312-326.

Garnett, E. R., M. L. Khandekar, 1992: The impact of large-scale atmospheric circulations and anomalies on Indian monsoon droughts and floods and on world grain yields—A statistical analysis. Agric. For. Meteor., 61, 113–128.

Green, P. 1996, Regional Analysis of Canada, Alaska, and Mexico Precipitation and Temperature for ENSO Impact, COAPS Report 96-6, Florida State University, Tallahassee, FL 32306-2840,p. 110.

Griffiths F.E., R.F. Lyndon, and M.D. Bennett. 1985. The effects of vernalization on the growth of the wheat shoot apex. Ann. of Bot. 56: 501-511.

Gomez-Macpherson, H.G. and R.A. Richards. 1995. Effect of sowing time on yield and agronomic characteristics of wheat in southeastern Australia. Aust. J. Agric. Res. 46: 1381-1399.

Gott M.B., F.G. Gregory, and O.N. Purvis. 1955**.** Studies in vernalization of cereals XIII. Photoperiodic control of stages in flowering between initiation and ear formation in vernalized and unvernalized `Petkus' rye. Ann. of Bot. 19: 87-126.

Hanson, K., G.A. Maul. 1991. Florida precipitation and the Pacific El Nino, 1985-1989. Florida Scientist 54: 160-168.

Hansen J.W., A. Hodges, J.W. Jones. 1998. ENSO influences on agriculture in the southeastern United States. J. Clim. 11:404–411.

Hansen J.W., J.W. Jones, A. Irmak, F. Royce. 2001. El Niño–Southern Oscillation impacts on crop production in the Southeast United States. In: Hatfield JL, Volenec JJ, Dick WA, Kral DM. (eds) Impacts of El Niño and climate variability on agriculture. ASA Special Publication no. 63. Madison, WI.

Hayman, P.T., A.M. Whitbread and D.L. Gobbett. 2010. The impact of El Niño Southern Oscillation on seasonal drought in the southern Australian grainbelt. Crop and Pasture Sci. 61:528-539.

Hildebrand, P., A. Caudle, V. Cabrera, M. Downs, M. Langholtz, A. Mugisha, R. Sandals, A. Shrair, and K. Beach. 1999. Potential Use of Long-Range Climate Forecasts by Agricultural Extension Agents in Florida: A Sondeo Report, Staff Paper SP 99-9. Food and Resource Economics Depatrment, University of Florida. pp 25.

Hoogenboom, G., J.W. Jones, P.W. Wilkens, C.H. Porter, K.J. Boote, L.A. Hunt, U. Singh, J.L. Lizaso, J.W. White, O. Uryasev, F.S. Royce, R. Ogoshi, A.J. Gijsman, and G.Y. Tsuji. 2010. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5 [CD-ROM]. University of Hawaii, Honolulu, Hawaii.

Hulme, M., E.M. Barrow, N.W. Arnell, P.A .Harrisson, T.C. Johns, T.E. Downing, 1999. Relative impacts of human-induced climate change and natural climate variability. Nature 397, 688–691.

Hunt, L.A., G. van der Poorten, aand S. Pararajasingham. 1991 Post anthesis temperature effects on duration and rate of grain filling in some winter and spring wheats. Can. J.of Plant Sci.71:609-617.

Incerti, M., and G.J. O'Leary. 1990. Rooting depth of wheat in the Victorian Mallee. Australian J. of Experimental Agric. 30: 817-824.

Jabrzemski, R and A. J. Sutherland. 2004. An innovative approach to weather-based decision-support for Agricultural models. Oklahoma Climate Survey.

Jenner, C.F. 1991. Effects of exposure of wheat ears to high temperature to dry matter accumulation and carbohydrate metabolism in the grain of two cultivars. I. Immediate response. Australian J.of Plant Physol. 18:165-177.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens,U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. DSSAT Cropping System Model. Eur. J. Agron. 18:235-265.

Kaufmann, R.K., Snell, S.E., 1997. A biophysical model of corn yield: integrating climatic and social determinants. Am. J. Agron. Econ. 79, 178–190.

Kiladis, G.N., H.F. Diaz. 1989. Global climatic anomalies associated with extremes in the southern oscillation. J. Climate 2: 1069-1090.

Langensiepen, M., H. Hanus, P. Schoop, and W. Grasle. 2008. Validating CERES-Wheat under North-German environmental conditions. Agric. Systems 97:34-47.

Levitt J. 1948. Frost killing and hardiness of plants. A critical review. Burgess Publishing Company. Minneapolis,Minnesota, USA.

Levy J, and M.L. Peterson. 1972. Response of spring wheat to vernalization and photoperiod. Crop Sci. 12: 487-490.

McBride, J. L. and Nicholls, N.: 1983, 'Seasonal Relationships between Australian Rainfall and the Southern Oscillation', *Mon. Wea. Rev.* 111, 1998–2004.

McLeod, J.G., C.A. Cambell, F.B. Dyck, and C.L. Vera. 1992. Optimum seeding dates of winter wheat in southwestern Saskatchewan. Agron. J. 84: 86-90.

Nain, A.S., V.K. Dadhwal, and T.P Singh. 2004. Use of CERES-Wheat model for yield forecast in central Indo-Gangetic Plains of India. J. Agric. Sci., Cambridge 142:59-70.

Nicholls, N. 1985. Towards the prediction of major Australian droughts. J. Climatol 5:553-56.

Nicholls, N. 1992. Historical El Niño/Southern Oscillation variability in the Australian region. In: Diaz, H.F. and V. Margraf (Eds.) El Niño, historical and paleoclimatic aspects of the Southern Oscillation. Cambridge University Press, Cambridge, UK, pp.151-174.

Olesen, J., T. Jensen, and J. Petersen. 2000. Sensitivity of field-scale winter wheat production in Denmark to climate variability and climate change. Climate Res. 15: 221-238.

Palmarola-Adrados, B., P. Chotěborská, M. Galbe, G. Zacchi. 2005. Ethanol production from non-starch carbohydrates of wheat bran, Bioresource Technology, 96 7:843-850 (http://www.sciencedirect.com/science/article/pii/S0960852404002640).

Paz, J.O., C.W. Fraisse, L.U. Hatch, A. Garcia y Garcia. L.C. Guerra, O. Uryasev, J.G. Bellow, J.W. Jones, and G. Hoogenboom. 2007. Development of an ENSO-based irrigation decision support tool for peanut production in the southeastern US. Comput. and Electronics in Agric.55:28-35.

Persson, T., A Garcia Y Garcia, J.O. Paz, C.W. Fraisse, and G. Hoogenboom. 2010. Reduction in green house gas emissions due to the use of bio-ethanol from wheat grain and straw produced in the south-eastern USA. J. Agric. Sci. 148:511-527.

Priestley, C.H.B., and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100:81-92.

Rasmussen, P.E., K. W. T. Goulding, J. R. Brown, P. R. Grace, H. H. Janzen, and M. Körschens. 1998. Long-Term Agroecosystem Experiments: Assessing Agric. Sustainability and Global Change Sci. 282:893-896.

Ruiz-Nogueira B., K.J. Boote, F. Sau.2001. Calibration and use of CROPGRO-soybean model for improving soybean management under rainfed conditions. Agric. Syst. 68 (2):151–173.

Ritchie, J., Singh, U., Godwin, D., Bowen, W. 1998. Cereal growth, development and yield. In: Tsuji, G., Hoogenboom, G., Thornton, P. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, Dordrecht, pp. 79–98.

Ropelewski, C.F., M.S. Halpert. 1986. North American precipitation and temperature patterns associated with the El Niño Southern-Oscillation (ENSO). Mon. Wea. Rev. 114: 2352-2362.

Ropelewski, C. F. and Halpert, M. S.: 1987, 'Global and Regional Scale Precipitation Patterns Associated with El Niño/Southern Oscillation', *Mon. Wea. Rev.* 115, 1606–1626.

Ropelewski, C. F. and Halpert, M. S.: 1996, 'Quantifying Southern Oscillation-Precipitation Relationships. *J. Climate* 9:1043–1059.

Sah, R.K. 1987. Tropical economies and weather information. In: Fein, J.S., P.L. Stephens (Eds.). Monsoons. John Wiley and Sons, New York, pp. 105-119.

Saseendran, S. A., L. Ma, D. C. Nielsen, M. F. Vigil, and L. R. Ahuja. 2005. Simulating planting date effects on corn production using RZWQM and CERES-Maize models. *Agron. J.* 97(1): 58-71.

Scherm, H., and X. B. Yang, 1995: Interannual variations in wheat rust development in China and the United States in relation to the El Nino/Southern Oscillation. Phytopathology. 85:970–976.

Sittel, M.C. 1994. Marginal Probabilities of the Extremes of ENSO Events for Temperature and Precipitation in the Southeastern United States. Technical Report 94-1. Center for Ocean-Atmospheric Prediction Studies, Florida State Univ., Tallahassee, Fla.

Slafer G.A., and H.M. Rawson. 1994. Sensitivity of wheat phasic development to major environmental factors: a reexamination of some assumptions made by physiologists and modelers. Austrailian J. of Plant Physiol. 4:785-497

Sofield, I., L.T. Evans, M.G. Cook, I.F. Wardlaw. 1977. Factors influencing the rate and duration of grain filling in wheat. Australian J.of Plant Physiol. 4:785-797.

Soler, C.M.T., P.C. Sentelhas, and G. Hoogenboom. 2007. Application of the CSM-CERES Maize model for planting date evaluation and yield forecasting for maize grown off-season in a subtropical enviroment. Eur. J. Agron.27:165-177.

Sun, H., X. Zhang, S. Chen, D. Pei, and C. Liu. 2007. Effects of harvest and sowing time on the performance of the rotation of winter wheat–summer maize in the North China Plain. Industrial Crops and Products 25: 239–247.

Tsuji, G.Y, G. Hoogenboom, P.K. Thorton (Eds.). 1998 Understanding Options for Agricultural Production. Kluwer Academic Publisher, Dorderecht, The Netherlands.

Tottman, D.R. 1977. The identification of growth stages in winter wheat with reference to the application of growth regulating herbicides. Ann. of Applied Biology 87: 213-224.

Wardlaw, I.F., I. Sofield, P.M. Cartwright. 1980. Factors limiting the rate of dry matter accumulation in the grain of wheat grown at high temperature. Australian J. of Plant Physiol. 7:387-400.

Watson, R., M. Zinyowera, R. Moss(Eds.), 1996. Climate Change 1995 — Impacts, Adaptation and Mitigation of Climate Change. Contribution of WG II to the Secon Assessment Report of the IPCC, Cambridge University Press, Cambridge.

Wheeler, T.R., G.R. Batts, R.H. Ellis, P. Hadley, J.I.L. Morison. 1996. Growth and yield of winter wheat (*Triticum aestivum*) crops in response to CO2 and temperature. J. of Agric. Sci., Cambridge 127:37-48.

Winter, S.R., and J.T. Musick. 1993. Wheat planting date effects on soil water extraction and grain yield. Agron. J. 85: 912-916

Xiong, W. D. Conway, I. Holman and E. Lin. 2008. Evaluation of Ceres-Wheat simulation of wheat production in China. Agron. J.100:1720-1728.

Zamora, D.S., S. Jose, J.W. Jones and W.P Cropper. 2009. Modeling cotton production response to shading in a pecan alleycropping system using CROPGRO. Agroforestry Systems 76:432-435.

II. Effect of Planting date and Cultivar Maturity on Wheat Yield and Yield Components

Abstract

Understanding the factors impacting wheat yield may lead to opportunities to increase yield potential. Climate variability has the ability to impact food production; however, farmers can adjust management practices to reduce climate-related risks. The objective of this study was to assess the effect of planting date and cultivars with different relative maturity levels on winter wheat production in Alabama. The study was conducted during 2009-2010 and 2010-2011 growing seasons at three research stations across Alabama: Tennessee Valley (TVS), Wiregrass (WGS), and E. V. Smith (EVS). Wheat was planted in a randomized complete block design with split-plots and five replications. Four planting dates at approximately 15 day intervals were assigned to the main plots, and three varieties with early (AGS 2060), medium (AGS 2035), and late maturity (Baldwin) were randomized within subplots. Results showed yield differences associated with location by planting date, maturity group and year interactions. Regardless of location and year, yield decreased as planting was delayed for the medium and late maturing varieties. This research demonstrated that average seed mass and yield could be increased if specific cultivars were planted 15 days earlier than the standard planting date used by farmers at each location. Varieties with medium and late maturities had the highest yield at all locations for the early planting dates.

The results from this study showed that the combination of relative maturity (cultivar) and planting date must be selected on a location basis. Both factors could eventually be modified according to the expected seasonal climate conditions. Data from

this study will be used to conduct simulation modeling to identify optimum planting date and maturity group for different climate scenarios including El Niño Southern Oscillation (ENSO) phases.

Introduction

Soft red wheat (*Triticum aestivum L.*) is an autumn sown crop in the southeastern United States (U.S.) used as a cover and/or forage or harvested for grain. It has recently gained special attention due to its potential as an ethanol feedstock (Beres et al., 2010). This increased interest along with the worldwide wheat demand represented on 190 million tons of net wheat imports by the year 2050 (FAO, 2006), suggest that wheat farmers might have to modify management practices in order to optimize and increase yield.

Planting date of wheat has been identified as a major factor impacting productivity (Cambell et al., 1991; McLeod et al., 1992; Sun et al., 2007). Changes in planting date result in differences in vernalization, and accumulation of temperature and precipitation by the plant throughout the growing season. These factors have influenced wheat yield potential by affecting the number of seed per unit area and weight per seed, factors that determine grain yield (Fisher, 1975; 1985; Sun et al., 2007). When winter wheat is planted early, the plant is exposed to longer periods of beneficial climatic and soil conditions, such as adequate soil moisture and increased temperatures, that are favorable for germination (Blue et al., 1990) which result in deeper root growth and favorable vegetative growth before colder weather arrives and decreases the growth rate. The increase in root and vegetative growth has many benefits including a well established crop cover of bare soil which results in less erosion and runoff, and higher water infiltration (Incerti and O'Leary, 1990; Winter and Musick, 1993). The down side of early fall planting dates is the increased risk for diseases such as wheat streak mosaic, high plains virus, barley yellow dwarf, sharp eyespot, common root rot, and take-all root rot as well as pests like hessian fly (Blue et al., 1990; Epplin et al., 1999). Studies conducted in Denmark indicate that earlier planting dates extend the growing season allowing total precipitation to increase which has a positive correlation with dry land wheat yield (Olesen et al., 2000). According to Olesen et al., (2000) an extended growing season is even more evident when wheat is planted in sandy soils due to low water holding capacity The influence of precipitation, amount and distribution, during the spring months seem to correlate also with higher yields (Rasmussen et al., 1998). Contrary to the benefits of early plantings, delayed planting could cause yield losses (Chen et al., 2002). Late planting dates have a tendency to experience more temperature fluctuations, which could shorten grain filling (Sofield et al., 1977; Wardlaw et al., 1980; Al-Khatib and Paulson, 1984; Hunt et al., 1991; Jenner, 1991; Slafer and Rawson, 1994), affect the duration of spike growth, increase spike sterility (Wheeler et al., 1996), and delay maturity if temperatures increase during pre- and post- anthesis growth stages.

Wheat cultivars have a broad range of vernalization requirements, some needing little to no cold treatment, such as spring wheat cultivars, while others have long requirements, such as hard red winter wheat cultivars. When a specific cultivar does not accumulate the amount of chill hours, flowering will not occur (Ahrens and Loomis, 1963; Chujo, 1966). Changes in planting date might interfere with vernalization requirements (Levitt, 1948; Aitken, 1961; Tottman, 1977). The effect of limited vernalization on wheat could affect the timing of floral initiation, number of leaves, timing of the emergence of the leaf flag, and number of total tillers (Griffiths et al., 1985; Brooking, 1996; Gott et al., 1955), which will impact vegetative growth (Levy and Peterson, 1972). Correctly matching wheat's phenology to the dominant environment would result in maximization of the adaptation and crop yield (Gomez-Macpherson and Richards, 1995). Therefore, farmers have to choose an appropriate planting date for a specific cultivar which will flower at the optimum time, hence reducing climate-related risks and increasing yield.

Vernalization requirements could be impacted by seasonal and inter-annual climate variability associated with the El Niño Southern Oscillation (ENSO). In the Southeast US during the El Niño phase of ENSO, warming of the equatorial Pacific's sub-surface ocean temperatures, lower than average ambient temperatures and above average precipitation are prevalent during winter and spring months. The contrary, La Niña phase, cooling of the equatorial Pacific's sub-surface ocean temperatures, result in increased temperature and precipitation below average values. These climatic variations associated with ENSO could then impact wheat growth and yield. Therefore, a better understanding of the effect planting date and cultivar maturity on wheat yield in the Southeast is needed in order to modify management practices to reduce climate related risks. The objective of this study was to determine the effect of planting date and cultivar selection on grain yield and yield components of winter wheat growing under the environmental conditions of three locations in Alabama.

Materials and Methods

Experimental Site and Treatments

A field experiment was conducted during 2009/10 and 2010/11 growing seasons at three Alabama Agricultural Experiment Station sites in North, Central, and South Alabama, namely the Tennessee Valley Research and Extension Center (TVS - North; Decatur silt loam soil) located in Belle Mina (34°41' N, 86°53'W), the E. V. Smith Research Center (EVS - Central; Compass loamy sand soil) located in Shorter (32°25' N, 85°53' W), and the Wiregrass Research and Extension Center (WGS - South; Dothan sandy loam soil) located in Headland (31°22' N, 85°18'51 W). The experimental design at each site was a randomized complete block (RCB) with a split-plot restriction on randomization with five replications. Four planting dates (PD) at approximately 15 d intervals were assigned to main plots (Table 1), and three cultivars with different maturing levels were randomized among subplots within each main plot. The three wheat cultivars used for this study were AGS 2060 (early maturity), AGS 2035 (medium maturity), and Baldwin (late maturity). Each subplot was 3.7 m wide by 9.1 m long with a row width of 17.8 cm. The seeding rate was 66 seeds per meter row, equivalent to 371 seed m^{-2}. All plots received a basal application of P, K, and lime based on recommendations of the Soil Testing Laboratory at Auburn University. Nitrogen fertilization consisted of 22.4 kg N ha^{-1} applied at planting and 112 kg N ha^{-1} applied at the Feekes 4 growing stage. Weeds, insects, and disease were chemically controlled as needed.

Measurements

Time until seedling emergence, anthesis, and physiological maturity were recorded. From each plot, a biomass sample from an area of 5 rows by 1 m length was cut at ground level at anthesis and at physiological maturity. Dry weights (after oven drying at 70^{o}C for at least 72 h) of stems, leaves and spikes were determined. Mature seed heads from each plot sample were counted and then individually threshed by hand. Seed was cleaned, weighed, and counted. The yield components derived from the biomass samples were: number of grains per square meter, average seed mass, and number of grains per seed head. At physiological maturity, an area 1.5 m wide x 9.1 m long in the middle of each plot was combine-harvested to obtain grain yield. Grain yield was converted to kg ha^{-1} and corrected to 13.5% moisture.

Weather data (2009-2011) including total daily precipitation (mm), and daily minimum and maximum ambient temperature (^{o}C) were obtained from the Agricultural Weather Information Service (AWIS) for each study location (Fig. 1).

Statistical Analysis

Annual data from each location were subjected to statistical analysis using a linear mixed model implemented in SAS® PROC GLIMMIX which was based on the underlying randomized complete block design with a split plot restriction on randomization. Treatment factors planting date (PD) and cultivar maturity as well as their interactions were considered fixed effects. Location and year and their interactions with treatment factors were also considered fixed effects. The reason for this is that the three locations behave in a rather consistent manner in regular wheat cultivar trials. Year has an intrinsic value because of its association with ENSO phase. Based on the design there were three random effects (1) Block(Location×Year); (2) PD* Block(Location×Year), the appropriate error term for planting date and its interactions with environmental effects; and (3) the residual variation, which is the appropriate error term for maturity and associated interactions with the remaining three factors. Since there was an *a priori* assumption that interactions should be an important source of variation, we used the critical *P*-value of 0.10 as cutoff. We used the Student Panel option in the GLIMMIX procedure to generate conditional residuals plots, which were then used to investigate the behavior of residuals. The normal assumption appeared reasonable in light of the residual structure; in two cases (seeds per square meter and average seed mass) one observation each was deleted from the dataset because of an unacceptably large (> 5) studentized residual.

Results and Discussion

Weather Conditions

The two growing seasons had different climatic conditions. El Niño phase of ENSO influenced the 2009/10 climatic conditions while; La Niña phase and the North Atlantic Oscillation (NAO) influenced the climatic conditions during the 2010/11 growing season. Independently of the location, lower temperatures and higher precipitation were observed during the 2009/10 season (El Niño year) compared to the 2010/11 season (La Niña year), which exhibited lower precipitation (Fig. 1).

Although wheat at each study location during 2009/10 was grown under decreased mean ambient temperature and increased mean precipitation with respect to the long-term average conditions (data not shown), differences in total precipitation during the months of September 2009 through June of 2010 existed between among the locations: North- 1108 mm, Central - 1358 mm, and South -1205 mm. Differences in precipitation among the locations were also observed at specific growth periods; the central location for example, had the highest amount of precipitation during the months of March through May, when wheat is transitioning from the vegetative stage to the reproductive stage, in contrast, the Northern location received less precipitation during the same period (Fig. 1). Differences also existed in average maximum and minimum ambient temperature during the months of September 2009 through June of 2010 between locations: North (18.8°C and 7.7°C), Central (21.9°C and 9.4°C), and South (23.3°C and 11.5°C), respectively (Fig. 1). The deviations of the maximum and minimum ambient temperature with respect to long-term average conditions (30 years) during the period September through June for the study locations were reported as 2.8°C and 2.9°C in the Northern location, 0.9°C and 0.2°C for Central, and 1.1°C and 0.1°C for Southern location. These data showed that the Southern location exhibited lower ambient temperatures with respect to the historic average values compared to the Northern location. Our data agree with Hansen et al. (1997) who observed an increase in total precipitation and a decrease in average maximum and minimum ambient temperature during El Niño years when studying the effect of ENSO on agriculture in the southeastern United States.

Overall, the 2010/11 season from September through June was dry and warm; however, temperatures for the months of December and January were below historic average values (data not shown). Although the wheat at each study location was grown under higher mean ambient temperature and lower precipitation with respect to the long-term average conditions, differences in total precipitation during the months of

September 2010 through June of 2011 existed among locations with the Northern location having higher precipitation (1111 mm) than the Central (646mm) and Southern (627 mm) locations. The Northern location also received multiple snow events, one tornado reached the experimental area, and several large thunderstorms, and this is the reason for the elevated total precipitation. The tornado caused some lodging in the plots corresponding to the first planting date. Differences in precipitation between the locations also existed during the months of March through May; transitioning from the vegetative to the reproductive stage of the wheat crop, with the Northern location receiving the highest amount of precipitation. Differences in average maximum and minimum ambient temperatures during the months of September 2010 through June of 2011 among the locations were as follows: North (20.3°C and 7.4°C), respectively; Central (23.8°C and 8.8°C), and South (25.3°C and 11.5°C). These values were above the 30 year average maximum and minimum ambient temperatures with deviations of the maximum and minimum temperature during the months of September through June at the study locations as follow: North - 1.4°C and 3.4°C, respectively; Central - 1.0°C and 0.6°C, respectively; and South - 1.1°C and 0.1°C respectively.

Grain Yield

The analysis of variance for yield data indicated differences in the main effects of year, planting date and the interaction location × year, and those accounted for 84% of the total treatment variation (data not shown). Adding the cultivar maturity effect and the location × cultivar maturity interaction, 93% of the total variation was accounted for, giving guidance for further analysis based on mixed models methodology. The location × year interaction ($P < 0.0001$) is of interest given the year-to-year climate variability that occurred during the duration of this study; the first crop year was influenced by El Niño phase while La Niña phase and the North Atlantic Oscillation (NAO) prevailed during the second crop year.

Wheat yield in the 2009/10 season (El Niño year) was 2031 kg ha^{-1} lower respect to the 2010/11 season (La Niña year) for all location-treatments combinations. During the 2010/11 season higher average yield compared to the 2009/10 season was observed in the central location (3031 kg ha^{-1} increment) followed by the northern (1616 kg ha^{-1} increment) and the southern (1446 kg ha^{-1} increment) locations (Table 2). During the spring months of March, April and May of 2011 (La Niña year), higher precipitation was observed at the Northern location with respect to the other two locations and compared to the precipitation records for the same months during the 2009/10 season (El Niño year). These differences in precipitation might explain yield differences between years and locations. Rasmussen et al. (1998) indicated that the distribution of precipitation is equally important as total precipitation during spring months, and that correlated well with higher yield.

Location × year × planting date was the highest-level significant interaction (P = 0.0527). Overall, yield decreased as planting was delayed (PD1 > PD2 > PD3 > PD4) for all location-year combinations, except at the central location in 2009, where PD3 had a higher yield than PD2 (Table 3). When compared to the current farmers' planting date (PD2), the latest planting date (PD4) resulted in a severe yield reduction ranging from 12% (North, 2010/11) to 29% (Central, 2009/10). On average, the earlier planting dates exhibited the highest yield for all locations-years. Planting 15 days earlier (PD1) than the farmers' planting date (PD2) never decreased yield but instead resulted in up to 28%

yield gain, except for the southern location in 2010/11. Our results were consistent with the findings from Bassu et. al (2009) and Subedi et al. (2007), who observed that earlier planting dates increase wheat grain yield in the Mediterranean and Canadian environments and also the results presented by Ferrise et. al. (2010) and Gomez-Macpherson and Richards (1995), who observed grain yield reduction as a result of delayed planting. Ferrise et. al. (2010) found a high correlation between higher yield and longer vegetative periods with greater precipitation events and early plantings rather than late winter plantings.

The location × cultivar maturity interaction was also significant ($P < 0.0001$), illustrating varietal differences in yield response to locations (environment). The medium and late maturing cultivars out-yielded the early maturing cultivar in the northern and southern locations by an average of 668 kg ha^{-1} and 206 kg ha^{-1}, respectively (Table 4). The yield advantage of the medium and late-maturing cultivars was more pronounced at the northern location, where both cultivars out-yielded the early maturing cultivar by 701 kg ha^{-1}, respectively. No significant differences were observed among cultivars at the central location, however, the medium maturing cultivar tended to have the greatest yield when compared to the early or late maturing cultivar. At the southern location, the medium maturing cultivar out yielded the early maturing cultivar by approximately 221 kg ha^{-1}.

Grain Yield Components

Number of Grains per Area

The analysis of variance for the number of grains per square meter indicated that the main effects of location, year, and the interaction location × year (environmental effects) accounted for 89% of the total treatment variation. The number of grains per square meter was significantly higher during the 2010/11 season (La Niña year) compared to the 2009/10 season (El Niño year) for central and southern locations while the opposite was observed at the northern location (Fig. 3). Abbate et al. (1997) observed that environmental factors such as incident of radiation, precipitation, temperature and photoperiod had a direct association to the number of grains per square meter, which could vary by location and year. The interactions location × year × cultivar maturity, cultivar maturity × planting date, location × planting date, and location × year, were significant ($P < 0.05$) sources of variation and accounted for 94% of the total treatment variation. There was a large amount of variation explained by location × year × cultivar maturity interaction with grains per square meter ranging from 5367 (Central-2009/10, Early maturing cultivar) to 20208 grain m^{-2} (Central-2010/11, Early maturing cultivar) (Table 2). Data showed that the number of grain per square meter changed between years and among locations irrespective of the cultivar with a ranking of North > South > Central and Central > North > South for the 2010/11 and 2009/10 seasons, respectively.

When the cultivars were compared across locations and years, the late maturing cultivar had the highest number of grains per square meter at all locations in the 2009/10 season and during the 2010/11 season the place was occupied by the early maturing cultivar. During the 2009/10 season, the early maturing cultivar exhibited lowest number of grain per square meter among all the locations; while, for the medium maturing cultivar the number of grains per square meter range was in between the late and early maturing cultivars for both location-years (Table 5). These results were consistent with Fisher’s (1983) observations that suggested that a cultivar with greater number of grains per square meter results from an increasing period of inflorescence (excluding grains) growth which was best observed on late maturating cultivars.

The interaction cultivar maturity × planting date illustrated cultivar differences in the number of grain per square meter as a response to planting date (Fig. 2). Among cultivars, the late maturing cultivar exhibited the highest number of grains per square meter across planting dates (PD2 through PD4); except for the earliest planting date (PD1). For the early maturing cultivar, there was a decreasing trend in the number of grains as planting was delayed. For the medium maturing cultivar there was no observable planting date trend, while for the late maturing cultivar the number of grains per square meter increased up to the second and third planting dates (PD2 and PD3) and considerably decreased with the last planting date. Compared with early and late maturing cultivars at PD1 and PD2, the medium maturing cultivar exhibited the lowest number of grains per square meter. The interaction between cultivar maturity × planting date observed on this study might be associated with the environmental conditions during the spike growth period which is related to the number of grains per square meter (Slafer et al., 1994; Bodega and Andrade, 1996). Therefore, changes in planting date and consequently vernalization conditions for flowering may result in changes on the timing of spike growth period impacting at the end the number of grain per square meter and final yield (Abbate et al., 1998). Data from this study agree with the results from Gomez-Macpherson et al (1995) who observed that as planting date was delayed the number of grains per square meter decreased.

When observing the location × planting date interaction ($P < 0.06$), the highest reduction in the number of grains per square meter was associated with late plantings

(PD4) regardless of location (Table 6). For the northern location, there was not a clear effect of planting date on the number of grains per area, however low grains per area were observed at PD4 compared to PD1 and PD3. In contrast, for the central and southern locations, a negative trend associated with delayed plating was observed. When planting 15 days before the farmers' customary planting date (PD2), an increase in the total number of grains per square meter at the central and southern locations was observed, while for the northern location, early planting had a negative effect compared to PD2. Compared to the farmers' customary planting date (PD2), the last planting date resulted in a severe reduction in the number of grains per square meter. These results agree with the work from Slafer and Rawson (1994) and Bodega and Andrade (1996) who observed that changes on planting date could shorten the spike growth period, which might result on a reduction on the number of grains per square meter. The importance of planting date and year effects on yield components have been studied by Bassu et al. (2009), who developed a yield model where the number of seeds per square meter explained 94% of total yield variation.

Average Seed Mass

Environmental effects of location, year, and the location × year interaction accounted for 50% of the total treatment variation (data not shown). Differences among locations for each of the study years (location x year interaction, $P < 0.001$) were observed (Fig. 4). Overall, average seed mass was higher in the northern location followed by the central and southern locations. The average seed mass was significantly higher during the 2009/10 season (El Niño year) compared to the 2010/11 season (La

Niña year) for central and southern locations while the opposite effect was observed at the northern location (Fig. 4).

The interactions location × year, year × cultivar maturity, and location × planting date × cultivar maturity were significant ($P < 0.05$) and accounted for 85% of the total treatment variation in the least squares analysis. Unlike yield and number of seed per square meter, cultivar maturity and its significant interactions with other effects accounted for 44% of the total treatment variation.

Seed mass differences existed between cultivars for both years of the study (year × cultivar maturity, $P = 0.0015$) with values ranging from 30.5 mg grain^{-1} (Early maturing variety - 2009/10) to 34.7 mg grain^{-1} (Medium maturing cultivar, 2010/11) (Fig. 5). The effect of cultivar maturity was quite consistent; in both crop years the medium maturing cultivar exhibited the highest average seed mass value compared to the other two varieties.

When average seed mass data was analyzed, it exhibited a significant location × planting date × cultivar maturity interaction ($P = 0.0568$) and values ranged from 26.6 mg grain^{-1} (Southern location- PD2-Late maturing cultivar) to 37.9 mg grain^{-1} (Northern location-PD2-Medium maturing cultivar) (Table 7). Average seed mass for the medium and late maturing cultivars tended to decrease as planting date was delayed for all locations, but changes in seed mass for the early maturing variety was not associated with planting date (Table 6). When comparing the first and the last planting dates (PD1 vs. PD4) for the medium maturing cultivar, average reduction in seed mass of 22%, 11% and 12% for the southern, central and northern locations, respectively, were observed. In eleven of twelve location-planting date combinations, the medium maturing cultivar had the highest average seed mass. Contrasting with the medium maturing cultivar, in eight of twelve location-planting date combinations the early-maturing cultivar had the lowest average seed mass and the seed mass values for the late maturing were in between the early and medium maturing cultivars. Knott and Talukdar (1971) and Stickler and Pauli (1964) observed similar trends of early planting dates increasing vegetative growth which resulted higher average seed mass, and Subedi et al. (2007) who associated yield reduction to late planting date via smaller average seed mass.

These results suggest that yield could be optimized via seed mass with the medium maturing cultivar being the best option. Also, increments of average seed mass could be achieved through early plantings of medium or late maturing cultivars especially during a season like 2010/11 with influence of La Niña phase of ENSO. Knott and Talukdar (1971), Abbate et. al. (1998), and McNeal et al. (1978) observed that increases in average seed mass were positively correlated with higher yield. For this current study, the higher grain yield observed for the medium maturing cultivar, the average seed mass suggest the high contribution of this yield component to final yield. Therefore, selection of management practices increasing average seed mass is desirable for improving wheat yields.

Grains per Spike

The analysis of variance for the number of grains per spike indicated that the environmental effects of location, year, location × year accounted for 74% of the total treatment variation (data not shown). The year effect, mainly associated with annual climatic conditions influenced by ENSO, on this yield component can be observed in Fig. 6, with lower number of grains per spike measured during the 2009/10 season (El Niño year) than 2010/11 (La Niña year), which was very similar to the effect observed on the number of grain per square meter variable. Besides the year effect, differences among locations by year were also observed. At the northern location, the highest number of grains per spike was measured during the 2009/10 season (El Niño year), while the central and southern locations were favored during the 2010/11 season (La Niña year). The interactions location × year, cultivar maturity × planting date, and location × year × planting dated were significant and accounted for 92% of the total treatment variation in the least squares analysis (data not shown).

Changes in the number of grains per spike between the varieties across planting dates were observed (cultivar maturity × planting date interaction, ($P = 0.04$). Independent of variety, the lowest number of seed per spike corresponded to the late planting date (PD4). For the early maturing cultivar, the highest number of seed per spike across the planting dates was observed, however, the number of seed per spike decreased as planting date was delayed (PD1 > PD2 > PD3 > PD4) (Fig. 7). For the medium maturing cultivar none trend was observed. In contrast, for the late maturing cultivar, the number of grains per spike increased until third planting date (PD3) and then decreased with the last planting date (PD4). Knapp and Knapp (1978) and Bassu et. al. (2009) observed similar results for the early and late maturing cultivars with later planting dates tending to have a reduced number of grains per spike due to low spike fertility. Evans et al. (1971) and Stickler and Pauli (1964) observed similar results to the medium maturing cultivar with planting date having little to no effect on the number of grains per spike.

Differences between varieties by location and year were also observed (location× year × cultivar maturity, $P < 0.001$). For five out of six location-year combinations, the early maturing cultivar exhibited on average the highest number of grains per spike (Table 8). The number of grains per spike on the late maturing cultivar was lower than the early maturing but higher than the medium maturing cultivar. In four out of six location-year combinations, the late maturing cultivar exhibited on average a higher number of grains per spike than the medium maturing cultivar. Knott and Talukdar (1971) found that the cultivar with the highest number of grains per spike was the least yielding, while the cultivar with the least number of grains per spike had the greatest yield. The results from this study agree with Knott and Talukdar (1971) in that the medium maturing cultivar had the lowest number of seed per spike but higher average seed mass and as a result the heighest yield. In contrast, the early maturing cultivar had the highest number of seed per spike but lowest average seed mass and lower overall yield.

Conclusion

The response of the yield and yield components for a specific cultivar to a particular planting date of a specific wheat variety is influenced by climatic conditions. As observed in the number of grain per square meter data, it is largely dependent on the specific year and location. During El Niño, temperatures decrease and precipitation increases in contrast with La Niña, which is characterized by increased temperature and reduced precipitation. This was observed during the 2010 growing which was classified as El Niño and the 2011 growing season which was classified as La Niña. The 2010/11 (La Niña) crop year resulted in a greater average seed mass compared to the 2009/10 (El Niño) season for 2/3 of the locations. Through the forecast ENSO phase, a proper selection of maturity group and planting date would help to optimize wheat yield.

The earlier planting dates tended to have increased average seed mass and the greatest yields for all locations and. However, the later planting dates tended to decrease grain per square meter. Planting before the standard planting date used by farmers in Alabama (planting date 2) would help to optimize wheat yield in both the medium and late maturities. The increase in yield is a response to an increasing the weight per seed both varieties.

For an early planting date for winter wheat, the use of a medium or late cultivar produced the greatest yields for all locations. If planting date must be delayed, an early maturity cultivar may produce the greatest yield, depending on location. The EVS and WGS locations show that this should be applied; while at the TVS location this trend was never observed.

Results from this study showed that relative maturity (cultivar) and planting date must be selected on a location basis for optimum yield. Both planting date and maturity could eventually be modified for each location according to predicted seasonal climate conditions. Data from this study will be used to conduct simulation modeling to identify optimum planting date and maturity group for different climate scenarios including different ENSO phases.

References

Abbate, P.E., F.H. Andrade, and J.P. Culot, P.S. Bindraban. 1997. Grain yield in wheat: Effects of radiation during spike growth period. Field Crops Res 54:245-257.

Abbate, P.E., F.H. Andrade, L. Lazaro, J.H. Bariffin, H.G. Berardocco, V.H. Indza, and F. Marturano. 1998. Grain yield increase in recent Argentine wheat cultivars. Crop Sci. 38:1203-1209.

Ahrens J.F., and W.E. Loomis. 1963. Floral induction and development in winter wheat. Crop Sci.3: 463-466.

Aitken Y. 1961. Flower initiation in relation to maturity in crop plants. I. Internode lengthening in relation to grazing oat varieties. Australian J. of Agric. Res.12: 389-396.

Al-Khatib K., and Paulsen G.M., 1984. Mode of high temperature injury to wheat during grain development. *Physiologia Plantarum* 61:363-368.

Bassu, S. Asseng, R. Motzo, F. Giunta.2009. Optimizing sowing date of durum wheat in a variable Mediterranean environment. Field Crops Res., 111:109–118.

Beres, B.L., K.N. Harker, G.W. Clayton, E. Bremer, R.E. Blackshaw, and R.J. Graf. 2010. Weed-Competitive Ability of Spring and Winter Cereals in the Northern Great Plains. Weed Tech. 24: 108-116.

Blue, E.N., S.C. Mason, and D.H. Sander. 1990. Influence of planting date, seeding rate, and phosphorus rate on wheat yield. Agron. J. 82: 762-768.

Bodega, J.L. and F.H. Andrade. 1996. The effects of genetic improvement and hybridization on grain and biomass yield of bread wheat. Cereal Res. Com. 24:171-177.

Brooking, I.R. 1996. Temperature Response of Vernalization in Wheat: A Developmental Analysis. Ann. Bot. 78: 507-512.

Cambell, C.A., F. Sellers, R.P. Zentner, J.G. McLoed, F.B. Dyck. 1991. Effects of seeding date, rate anddepth of winter wheat grown on conventional fallow in Southwestern Saskatchewan. Can. J. of Plant Sci. 71:51-61.

Chen, C., W.A. Payne, R.W. Smiley, M.A. Stoltz. 2002. Yield and water-use efficiency of eight wheat cultivars planted on seven date in northeastern Organ. Agron. J. 95:836843.

Chujo H. 1966. Difference in vernalization effect in wheat under various temperatures. J. of the Crop Sci. Society of Japan 35: 177-186.

Epplin, F.M., I. Hossain, and E.G. Krenzer Jr. 1999. Winter wheat fall-winter forage yield and grain yield response to planting date in a dual-purpose system. Agric. Systems 63: 161-173.

Evans, R.G.,K.E. Bohnenblust, B.J. Kolp, and G.P. Roehrkasse. 1971. Yield and yield components of winter barley as affected by variety and planting date. Wyoming Agric. Exp. Stn. Res. J. 49.

Ferrise, R, A. Triossi, P. Strantonovitch, M. Bindi, and P. Martre. 2010. Sowing date and nitrogen fertilization effects on dry matter and nitrogen dynamics for durum wheat: An experimental and simulation study. Field Crops Res. 117:245-257.

Fisher, R.A. 1975. Yield potential in dwarf wheat and the effect of shading. Crop Sci. 15: 607-613.

Fisher, R.A. 1983. Growth and yield of wheat. In W.H. Smith and S.J. Bante (ed.) Potential productivity of field crops under different environments. International Rice Research Institution, Los Baños, Philippines. p. 129-154.

Fisher, R.A. 1985. Number of Kernels in wheat crops and the influence of solar radiation and temperature. J. Agric.Sci., Cambridge 105: 447-46.1

FAO. 2006. World agriculture: towards 2030/2050. Food and Agriculture Organization of the United Nations. http://www.fao.org/fileadmin/user_upload/esag/docs/Interim_report_AT2050web.pdf (accessed 05 Jun. 2012)

Griffiths F.E., R.F. Lyndon, and M.D. Bennett. 1985. The effects of vernalization on the growth of the wheat shoot apex. Ann. Bot. 56: 501-511.

Gomez-Macpherson, H.G. and R.A. Richards. 1995. Effect of sowing time on yield and agronomic characteristics of wheat in southeastern Australia. Aust. J. Agric. Res. 46: 1381-1399

Gott M.B., F.G. Gregory, and O.N. Purvis. 1955**.** Studies in vernalization of cereals XIII. Photoperiodic control of stages in flowering between initiation and ear formation in vernalized and unvernalized `Petkus' rye. Ann. Bot. 19: 87-126.

Hansen J.W., A.W. Hodges, and J.W. Jones. 1997. ENSO influences on Agriculture in the Southeastern United States. Am. Meteorol.Soc. J. 11:404-411.

Hunt, L.A., G. van der Poorten, and S. Pararajasingham. 1991 Post anthesis temperature effects on duration and rate of grain filling in some winter and spring wheat. Can. J. of Plant Sci.71:609-617.

Incerti, M., and G.J. O'Leary. 1990. Rooting depth of wheat in the Victorian Mallee. Australian J. Experimental Agric.30: 817-824.

Jenner, C.F. 1991. Effects of exposure of wheat ears to high temperature to dry matter accumulation and carbohydrate metabolism in the grain of two cultivars. I. Immediate response. Australian J. of Plant Physol. 18:165-177.

Knapp, W.R. and J.S. Knapp. 1978. Response of winter wheat to date of planting and fall fertilization. Agron. J. 70:1048-1053.

Knott, D.R. and B. Talukdar. 1971. Increase seed weight in wheat and its effect on yield, yield components, and quality. Crop Sci.11:280-283.

Levitt J. 1948. Frost killing and hardiness of plants. A critical review. Burgess Publishing Company. Minneapolis,Minnesota, USA.

Levy J, and M.L. Peterson. 1972. Response of spring wheat to vernalization and photoperiod. Crop Sci. 12: 487-490.

McLeod, J.G., C.A. Cambell, F.B. Dyck, and C.L. Vera. 1992. Optimum seeding dates of winter wheat in southwestern Saskatchewan. Agron. J. 84: 86-90.

McNeal, F.H., C.O. Qualset, D.E. Baldridge, and V.R. Stewart. 1978. Selection for Yield and Yield Components in Wheat. Crop Sci. 18:795-799.

Olesen, J., T. Jensen, and J. Petersen. 2000. Sensitivity of field-scale winter wheat production in Denmark to climate variability and climate change. Climate Res. 15: 221-238.

Rasmussen, P.E., K. W. T. Goulding, J. R. Brown, P. R. Grace, H. H. Janzen, and M. Körschens. 1998. Long-Term Agroecosystem Experiments: Assessing Agric. Sustainability and Global Change Sci. 282:893-896.

SAS Institute. 2011. SAS 9.3 Product Documentation (http://support.sas.com/documentation/93/index.html; verified 3. January, 2012).

Slafer G.A., and H.M. Rawson. 1994. Sensitivity of wheat phasic development to major environmental factors: a reexamination of some assumptions made by physiologists and modelers. Austrailian J. of Plant Physiol. 4:785-497.

Sofield, I., L.T. Evans, M.G. Cook, I.F. Wardlaw. 1977. Factors influencing the rate and duration of grain filling in wheat. Australian J. of Plant Physiol. 4:785-797.

Stickler, F.C., and A.W. Pauli. 1964. Yield and winter survival of winter barley varieties as affected by date and rate of planting. Crop Sci.4:487-488

Subedi, K.D., B.L. Ma, A.G. Xue. 2007. Planting date and nitrogen effects on grain yield and protein content of spring wheat. Crop Sci. 47 (2007), pp. 36–44

Sun, H., X. Zhang, S. Chen, D. Pei, and C. Liu. 2007. Effects of harvest and sowing time on the performance of the rotation of winter wheat–summer maize in the North China Plain. Industrial Crops and Products 25: 239–247.

Tottman, D.R. 1977. The identification of growth stages in winter wheat with reference to the application of growth regulating herbicides. Ann. of Applied Biology 87: 213-224.

Wardlaw, I.F., I. Sofield, P.M. Cartwright. 1980. Factors limiting the rate of dry matter accumulation in the grain of wheat grown at high temperature. Australian J. of Plant Physiol. 7:387-400.

Wheeler, T.R., G.R. Batts, R.H. Ellis, P. Hadley, J.I.L. Morison. 1996. Growth and yield of winter wheat (Triticum aestivum) crops in response to CO_2 and temperature. J. of Agric. Sci., Cambridge 127:37-48.

Winter, S.R., and J.T. Musick. 1993. Wheat planting date effects on soil water extraction and grain yield. Agron. J. 85: 912-916

Table 1. Planting dates for the experiment which was conducted in North, Central, and South Alabama during the 2009/10 and 2010/11 cropping seasons.

	Planting Date			
Year/ Location	1	2[†]	3	4
2009/10				
TVS - North	Oct. 17	Oct. 29	Nov. 15	Nov. 30
EVS – Central	Oct. 21	Nov. 8	Nov. 22	Dec. 5
WGS - South	Nov.2	Nov. 16	Nov. 30	Dec. 11
2010/11				
TVS - North	Oct. 15	Oct. 30	Nov. 15	Nov. 30
EVS – Central	Oct. 23	Nov. 6	Nov. 20	Dec. 5
WGS - South	Oct. 29	Nov. 13	Nov. 26	Dec. 10

[†] Current Recommended planting date for winter wheat in Alabama.

Table 2. Effect of year and location on winter wheat yield (kg ha^{-1}) in the 2009/10 and 2010/11 cropping seasons.

				Sim. adj. P-value vs.	
Year/ Location	Yield	SE[†]	Rank[‡]	Central	South
	--- kg ha^{-1} ---				
2009/2010					
North	2292	63.6	1	<0.0001	0.0304
Central	1760	56.9	3		0.0041
South	2055	56.9	2		
2010/2011					
North	3908	56.9	2	<0.0001	0.0002
Central	4791	56.9	1		<0.0001
South	3502	56.9	3		

[†] Standard Error
[‡] Yield ranked from highest to lowest

Table 3. Effect of planting date on winter wheat yield (kg ha^{-1}) at three experimental sites in the 2009/10 and 2010/11 cropping seasons.

		Planting date							
		1		2		3		4	
Location	Year	Yield	SE†	Yield	SE†	Yield	SE†	Yield	SE†
		------------------------------------- kg ha^{-1} ----------------------------------							
North	2009/10	6604	232.9	5917	232.9	5729	232.9	4648	232.9
North	2010/11	4154	208.3	4113	208.3	3764	208.3	3589	208.3
Central	2009/10	5190	216.0	4537	208.3	4913	208.3	3229	208.3
Central	2010/11	5284	208.3	5281	208.3	4681	208.3	3902	208.3
South	2009/10	5708	208.3	5377	208.3	4950	208.3	4504	208.3
South	2010/11	4490	208.3	3494	208.3	3242	208.3	2770	208.3

† Standard Error

Table 4. Effect of cultivar maturity on winter wheat yield (kg ha^{-1}) at three experimental sites in the the 2009/10 and 2010/11 cropping seasons.

			Sim. adj. *P*-value vs.	
Location/ Cultivar Maturity	Yield	SE[†]	Medium	Late
	--- kg ha^{-1} ---			
North				
Early	2654	77.4	<0.0001	<0.0001
Medium	3289	77.4		0.8150
Late	3356	77.4		
Central				
Early	3289	73.0	0.8352	0.5992
Medium	3349	73.0		0.2757
Late	3188	73.0		
South				
Early	2641	73.0	0.0926	0.1578
Medium	2862	73.0		0.9615
Late	2833	73.0		

[†] Standard Error

[‡] Yield ranked from highest to lowest

Table 5. Effect of cultivar maturity, location and year on number of grains per m^{-2} in the 2009/10 and 2010/11 cropping seasons.

		No. Grains per m^{-2}			Contrast P-value vs.	
Year/Location	Cultivar maturity	Mean	SE[†]	Rank[‡]	Medium	Late
		------ seeds m^{-2} -------				
2009/2010						
North	Early	14689	681	3	0.487	0.003
North	Medium	15559	681	2		0.078
North	Late	17229	681	1		
Central	Early	5367	609	3	0.967	0.836
Central	Medium	5541	609	2		0.947
Central	Late	5757	609	1		
South	Early	7061	609	2	0.600	0.012
South	Medium	6383	622	3		0.000
South	Late	9111	635	1		
2010/2011						
North	Early	14322	622	1	0.729	0.640
North	Medium	13793	609	2		0.990
North	Late	13697	609	3		
Central	Early	20208	609	1	0.000	0.026
Central	Medium	17273	609	3		0.222
Central	Late	18420	609	2		
South	Early	12417	622	2	0.726	0.999
South	Medium	11880	622	3		0.697
South	Late	12443	609	1		

[†] Standard Error

[‡] Number of grains per m^{-2} ranked from highest to lowest

Table 6. Effect of planting date on the number of grains per m^{-2} at three experimental sites averaged of the data collected during the 2009/10 and 2010/11 cropping seasons.

					Sim. adj. P-value vs.		
Loc	(PD)	Grains m^{-2}	SE[†]	Rank[‡]	PD2	PD3	PD4
North	1	14500	513	3	0.7334	0.1118	0.8305
North	2	15146	520	2		0.6179	0.2440
North	3	15908	513	1			0.0129
North	4	13972	513	4			
Central	1	13009	484	1	0.6873	0.7841	0.0004
Central	2	12363	484	3		0.9983	0.0114
Central	3	12464	484	2			0.0075
Central	4	10541	484	4			
South	1	10908	506	1	0.3518	0.5148	0.0018
South	2	9914	491	3		0.9924	0.1281
South	3	10080	491	2			0.0664
South	4	8628	484	4			

[†] Standard Error

[‡] Number of grains per m^{-2} ranked from highest to lowest

Table 7. Effect of planting date and cultivar maturity on the average seed mass at three experimental sites in the 2009/10 and 2010/11 cropping seasons.

				Sim. adj. P-value vs.		
Location/Planting date	Cultivar Maturity	Average seed mass	SE[†]	Rank[‡]	Medium	Late
		—— mg ——				
North						
1	Early	32.8	1.01	3	0.0014	0.0862
1	Medium	37.9	1.01	1		0.2775
1	Late	35.8	1.01	2		
2	Early	32.1	1.06	3	0.0034	0.8008
2	Medium	36.8	1.01	1		0.0201
2	Late	33.0	1.01	2		
3	Early	32.9	1.01	3	0.1590	0.9917
3	Medium	35.5	1.01	1		0.1992
3	Late	33.1	1.01	2		
4	Early	29.9	1.01	3	0.0765	0.2505
4	Medium	33.0	1.01	1		0.8245
4	Late	32.2	1.01	2		
Central						
1	Early	31.1	0.95	3	0.0001	0.0026
1	Medium	36.7	0.95	1		0.6861
1	Late	35.6	0.95	2		
2	Early	32.6	1.01	3	0.0073	0.2962
2	Medium	36.8	0.95	1		0.2536
2	Late	34.7	0.95	2		
3	Early	29.2	0.95	3	0.0000	0.0347
3	Medium	35.7	0.95	1		0.0530
3	Late	32.5	0.95	2		
4	Early	31.0	0.95	2	0.3580	0.6305
4	Medium	32.8	0.95	1		0.0621
4	Late	29.7	0.95	3		
South						
1	Early	29.9	1.01	3	0.0006	0.9282
1	Medium	35.3	1.01	1		0.0020
1	Late	30.5	1.01	2		
2	Early	28.7	0.95	2	0.0000	0.2374
2	Medium	34.9	1.01	1		0.0000
2	Late	26.6	0.95	3		
3	Early	30.2	0.95	2	0.7168	0.2043
3	Medium	31.2	0.95	1		0.0377
3	Late	27.8	1.01	3		
4	Early	29.6	0.95	1	0.2059	0.2460
4	Medium	27.3	0.95	3		0.9945
4	Late	27.5	0.95	2		

[†] Standard Error

[‡] Average seed mass ranked from highest to lowest

Table 8. Effect of cultivar maturity on the number of seeds per spike at three experimental sites in the 2009/10 and 2010/11 cropping seasons.

		No. Grains per spike			Contrast P-value vs.	
Year/Loc	Maturity	Mean	SE[†]	Rank[‡]	Medium	Late
		----- Grains spike^{-1} ---				
2009/2010						
North	Early	35	1.08	1	<0.0001	0.178
North	Medium	29	1.08	3		0.079
North	Late	32	1.08	2		
Central	Early	19	1.04	1	0.567	0.472
Central	Medium	18	1.01	2		0.988
Central	Late	17	1.01	3		
South	Early	26	1.01	1	<0.0001	0.003
South	Medium	18	1.04	3		0.124
South	Late	21	1.07	2		
2010/2011						
North	Early	28	0.99	1	0.063	0.260
North	Medium	25	0.97	3		0.737
North	Late	26	0.97	2		
Central	Early	35	1.01	1	<0.0001	0.063
Central	Medium	30	1.01	3		0.136
Central	Late	32	1.01	2		
South	Early	26	1.04	3	0.790	0.479
South	Medium	27	1.04	2		0.877
South	Late	27	1.01	1		

[†] Standard Error

[‡] Number of seeds per spike ranked from highest to lowest

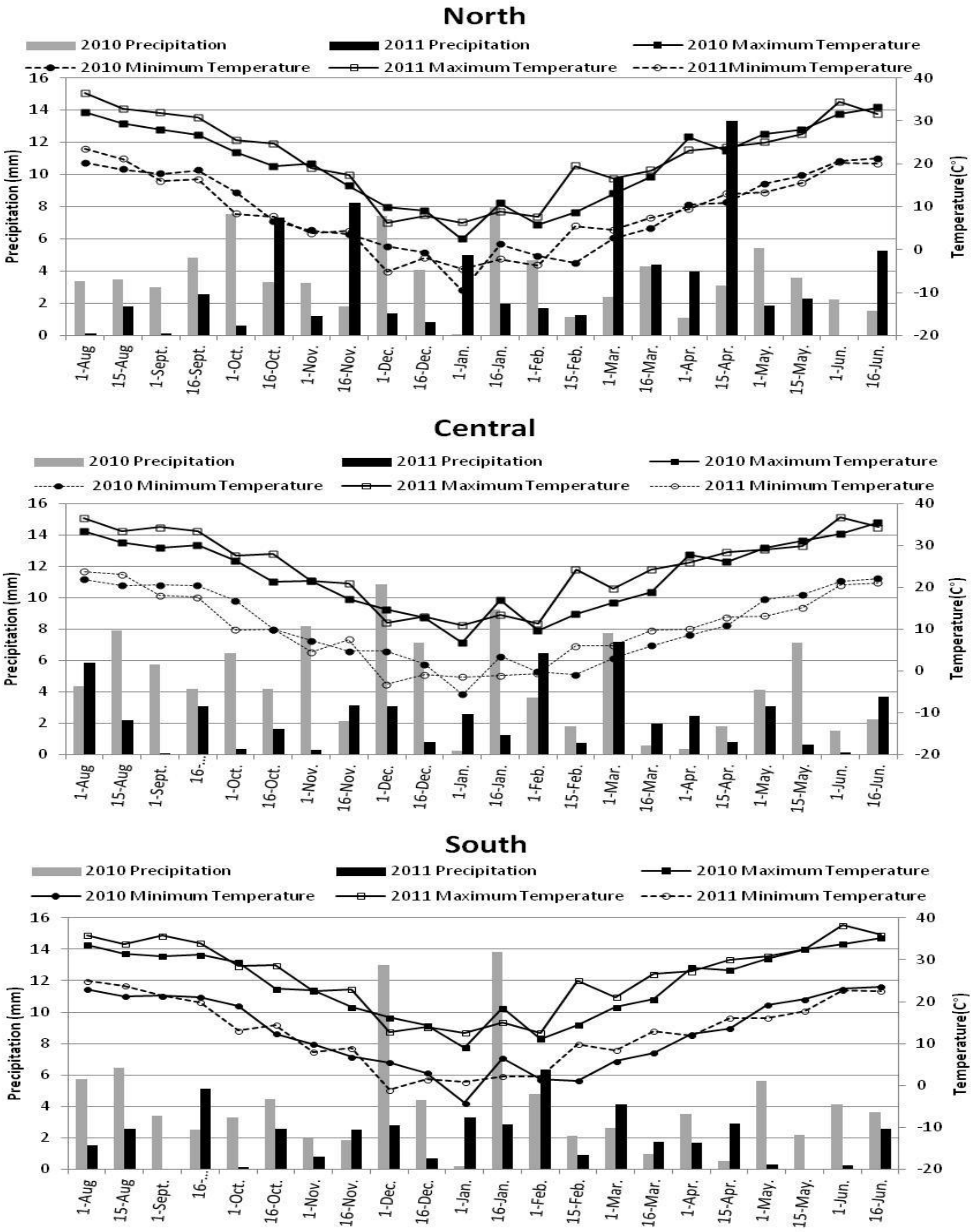

Fig. 1. Average maximum and minimum temperature (^{o}C) and total precipitation (mm) for the 2009/10 and 2010/11 winter wheat growing seasons at three experimental sites in Alabama.

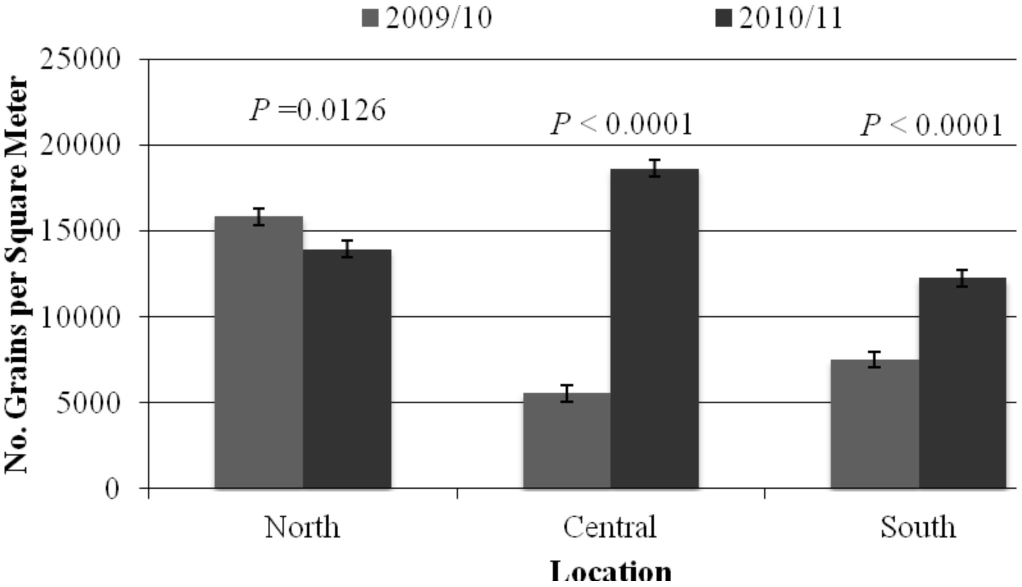

Fig. 2. Effect of year and location on the number of grains per m^{-2} during the 2009/10 and 2010/11 cropping seasons.

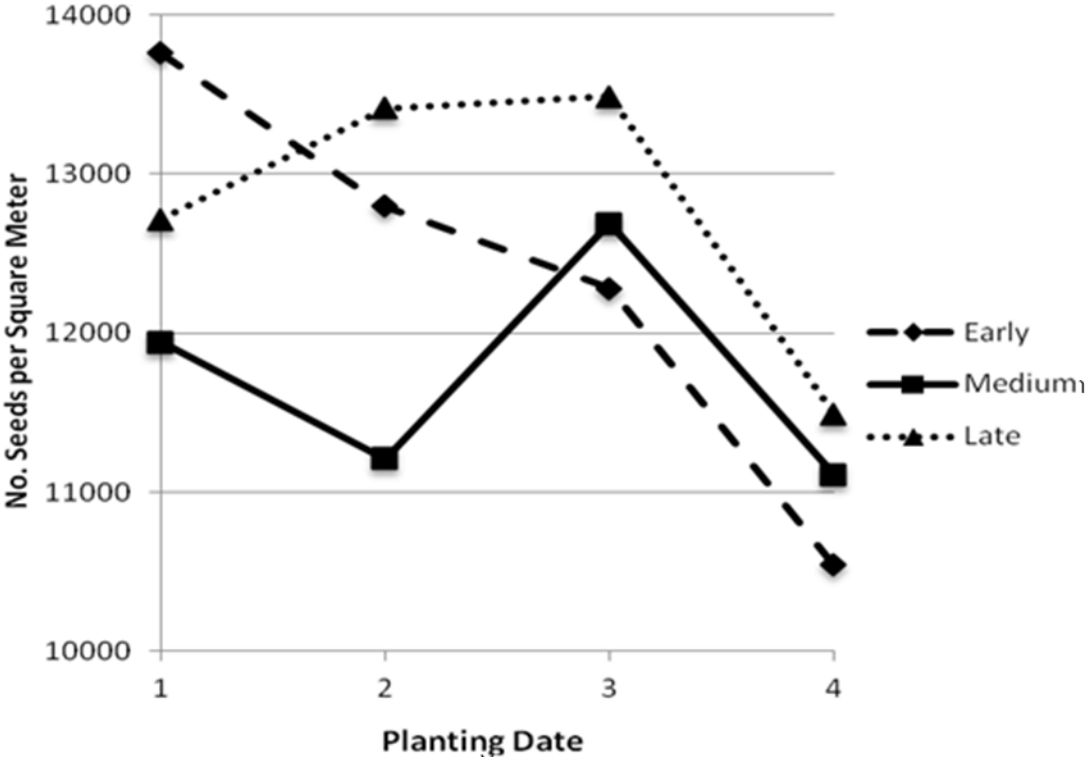

Fig. 3. Effect of planting date on number of grains per m^{-2} of three wheat varieties planted at three experimental sites in Alabama during the 2009/10 and 2010/11 cropping seasons.

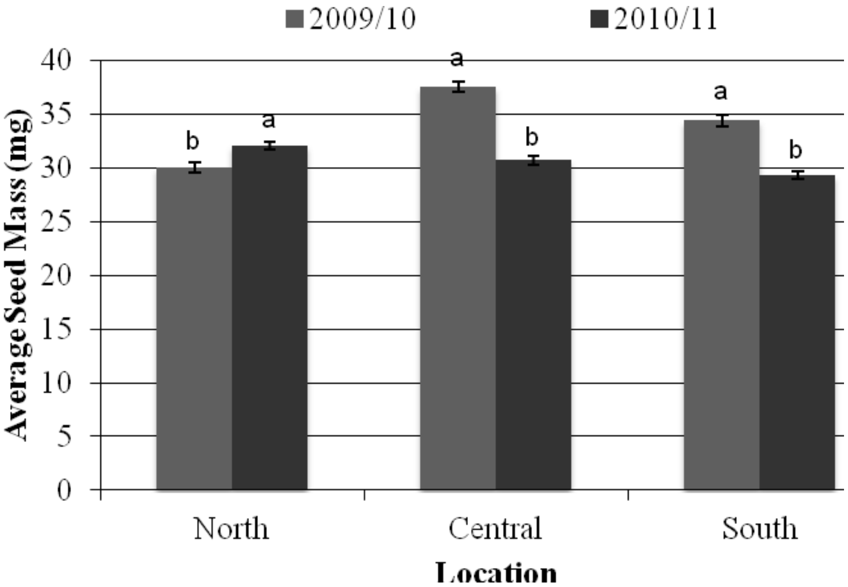

Fig. 4. Effect of the location on the average seed mass during the 2009/10 and 2010/11 cropping seasons.

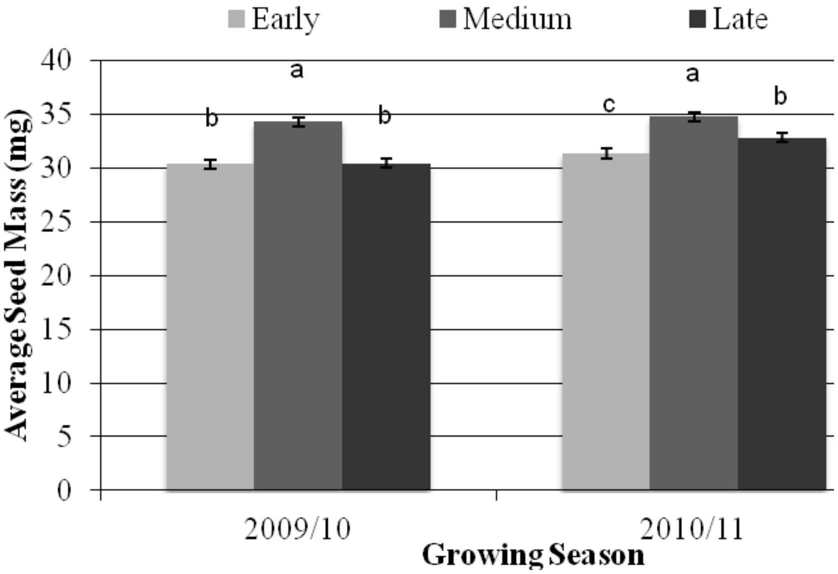

Fig. 5. Effect of cultivar maturity of the average seed mass (mg) across experimental sites for the the 2009/10 and 2010/11 cropping seasons.

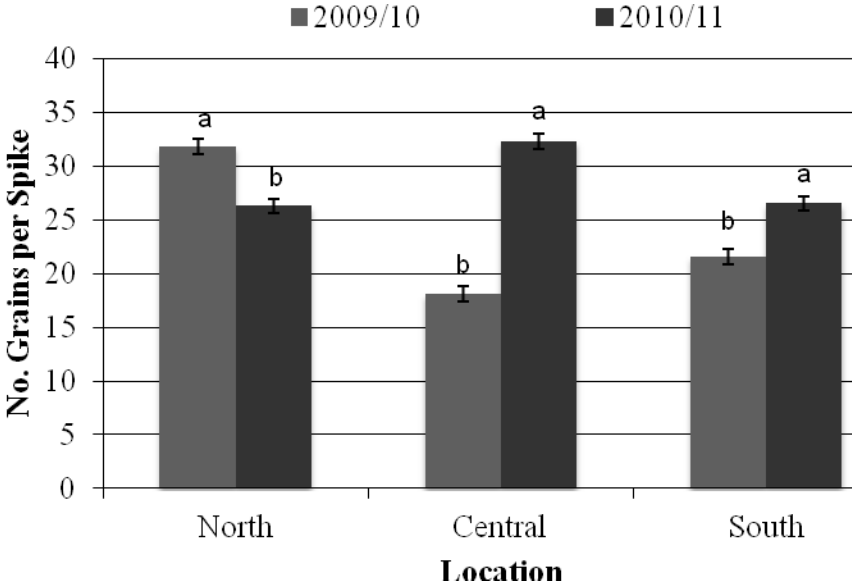

Fig. 6. Effect of the number of grains per spike planted at three locations in Alabama during the 2009/10 and 2010/11 cropping seasons.

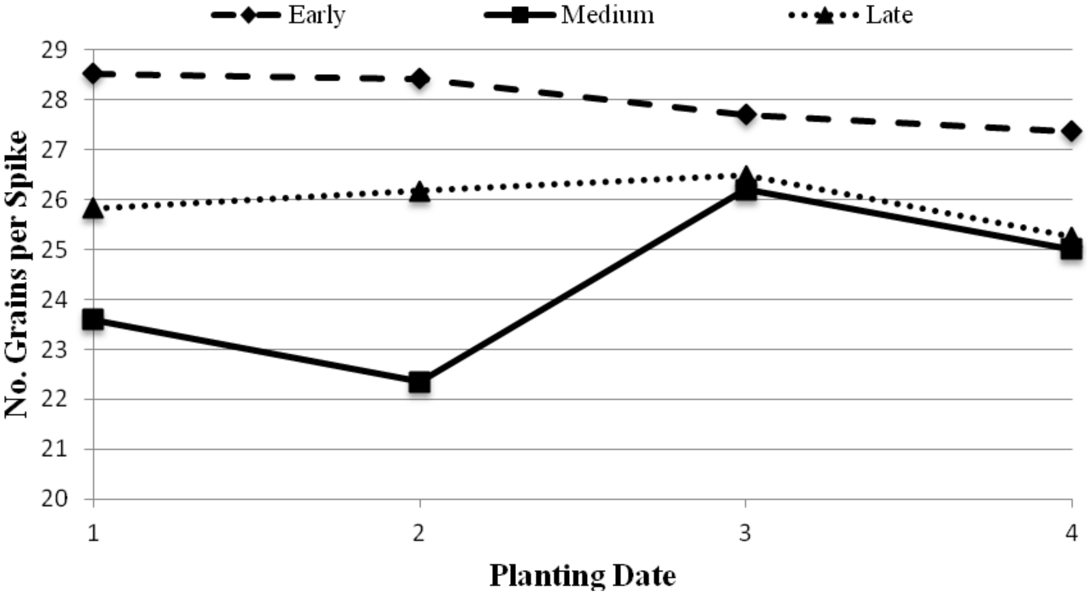

Fig. 7. Effect of planting date on the number of grains per spike for three wheat cultivars with early, medium and late maturity levels planted across three experiment site in Alabama during the 2009/10 and 2010/11 cropping seasons.

III. Simulate Wheat Yield Response to Planting Date and Cultivar Selection for El Niño-Southern Oscillation (ENSO) in Alabama

Abstract

Variability in climatic conditions during the wheat (*Triticum aestivum L.*) growing season in the Southeastern United States is strongly influenced by El Niño-southern Oscillation (ENSO). Hence, ENSO forecast could potentially be used as a tool to adjust wheat management practices, which can be identified through the use of a crop simulation model. The objectives of this study were to evaluate the Cropping System Model (CSM)-CERES-Wheat for its ability to simulate growth, development, and grain yield of three different wheat varieties planted at three locations, (Belle Mina, Shorter, and Headland) in Alabama, and to use the model to determine the impact of changes in planting date and variety selection combination based on ENSO phases. The CSM-CERES-Wheat model was calibrated using data from three field studies, which were conducted during the 2009/2010 and 2010/2011 growing seasons. Data for the model evaluation were compiled from the 2008-2011 Alabama Performance Comparison of Small Grain Variety Trails. A seasonal analysis using 60 years of daily historic weather data was used to identify the impact of planting date and variety selection on wheat yield as well as the yield differences between ENSO phases. Simulation results show that yield for all varieties decreased as planting was delayed at Headland and Belle Mina, while for Shorter, simulated average yield for the medium and late maturing varieties, AGS 2035

and Baldwin varieties, tended to be higher for later planting dates. In contrast, for the early maturing variety, AGS 2060, there was not yield variation between planting dates. During the La Niña years, the highest simulated wheat yield was observed compared to the other ENSO phases across all locations. The risk for yield losses associated with delayed planting was higher during El Niño phase than the other ENSO phases, especially for the early maturing variety. In contrast, during La Niña and Neutral phases the AGS 2060 variety, exhibited the lowest yield reduction associated to late planting compared to the AGS 2035 and Baldwin varieties. At Shorter, there was not a clear trend for higher yield associated with the specific variety to ENSO phase. As for Headland, AGS 2060, exhibited the highest yield reduction (16.9%), followed by AGS 2035 (16.25%) and Baldwin (12.8%) during the El Niño years, AGS 2060 (Table 9). During the La Niña years, there was not a broad range of yield reduction differences between the varieties with the AGS2060 having the lowest yield reduction (10.45%) followed by Baldwin (11.89%) and AGS 2035 (12.32%). Neutral years exhibited a broad range of yield reduction differences between the locations and varieties. For Belle Mina, the AGS2060 had the lowest yield reduction (18.89%) followed by Baldwin (24.17%) and AGS 2035 (25.44%). Further studies should focus on the evaluation and application of the wheat model for other management practices and other agroclimatic regions where wheat is an important crop.

Introduction

Many studies have indicated that some changes in ambient temperature and precipitation are strongly associated with El Niño Southern Oscillation (ENSO) (Ropelewski and Halpert, 1986). El Niño, the warm phase of ENSO, is described as a warming on the equatorial Pacific Ocean surface temperatures, which causes a reduction in ambient temperature, solar radiation, and higher precipitation in the southeastern United States (Hansen et al., 1998). In contrast, a cooling on the equatorial Pacific Ocean sea surface temperature described as La Niña phase of ENSO is related to an increase in temperature and decrease in precipitation in the Southeast United States. The impact of ENSO phases on weather patterns is evident in the fall and spring seasons and stronger during the winter season (Ropelewski and Halpert, 1986; Kiladis and Diaz, 1989; Hanson and Maul, 1991; Sittel, 1994). Due to the importance of soil moisture and vernalization requirements in wheat, seasonal and interannual climatic variations associated with ENSO could impact wheat production.

In the Southeast United States, production, price fluctuations, and ability to harvest row crops such as corn (*Zea mays* L.), soybean (*Glycine max* L.), peanut (*Arachis hypogaea* L.), cotton (*Gossypium hirsutum* L.) and wheat (*Triticum aestivum* L.); as well as yield reductions for several horticultural and row crops including bell peppers (*Capsicum annum* L.), and tomatoes (*Solanum lycopersicum* L.) have been associated with ENSO phases (Hansen et al., 1998; Hansen et al., 2001). In Australia, South Asia, and the mid-North America, ENSO has been found to have an adverse impact on cereal production which includes risks for diseases like wheat rust (Garnett and Khandekar, 1992; Scherm and Yang, 1995) and yield losses (Nicholls, 1985; Nicholls, 1992; Hayman et al., 2010).

Forecast for ENSO can be used to help decide which management practices and other agricultural decisions could be implemented to optimize yield and increase profits (Hildebrand et al., 1999). Climate forecast has been shown to benefit agricultural systems by changing management practices such as planting dates (Soler et al., 2007), nitrogen application (Asseng et al., 2011), fungicide application (Hildebrand et al., 1999) and others for minimizing the adverse impacts or maximizing the beneficial impact on crop yield. Cusack (1983) and Sah (1987) suggested that the use of climate forecasting could lead to the next ‘Green Revolution’. Adams et al., (1995) estimated in $100 million the annual economic benefits of ENSO-driven climate forecasting in the southeast agricultural systems.

Soft red wheat is a crop often planted during the winter in the southeastern United States and is used as a cover and/or forage crop or harvested for grain. Due to increased demand for soft red wheat and the strength of ENSO during the wheat-growing months in the southeast (Hansen et al., 1998), it is important to identify ENSO based management practices for wheat yield optimization (Adams et al., 1995).

Changes in climate variability can be beneficial or detrimental for wheat growth and development (Boyer, 1982). Bakker et al. (2005) concluded that an increase in temperature will limit vernalization and enhance wheat development rate leading to a reduction in the growing period. The limited vernalization on wheat has shown effects on the timing of floral initiation, number of leaves, timing of the emergence of the leaf flag, and number of total tillers (Griffiths et al., 1985; Brooking, 1996; Gott et al., 1955), which affect the amount of vegetative growth observed (Levy and Peterson, 1972). Precipitation tends to have a positive correlation with dry land wheat yield being more evident on sandy soils due to their typically low water holding capacity (Olesen et al., 2000). Rasmussen et al. (1998) indicated that the distribution of precipitation is equally important as total precipitation. When precipitation is partially distributed during the spring months, higher yields could be expected (Rasmussen et al., 1998). Several scientists have shown that photoperiod affects the number of wheat leaves on the main stem which can result in a significant yield reduction (Baker et al.,1980; Bauer et al.,1984; Delécolle et al., 1985).

Increasing wheat yield and reducing yield variability due to climatic influences may be possible through changes in management practices. According to Chen et al. (2002) for example, if favorable climatic and soil conditions exists, earlier planting dates can result in greater yield than late plantings. An understanding of how management practices (e.g., variety selection, planting date, fertilization) could be adjusted based on ENSO phases is crucial so farmers can take advantage of favorable conditions or reduce climatic related risks. Identification of changes on management practices through field experimentation might take several years of data collection before reaching definite conclusions. In recent years, crop models have been used for the support of agronomic research, field agronomic advice, and decision support for agricultural policy formulation (Boote et. al., 1996).

Crop modeling along with short term field experiments could be used to improve agronomic management and/or quantify yield losses associated with biotic stress, as well as tools for the evaluation of alternative management practices for a particular location over a broad range of seasons and also to assess long-term climate risks on crop yield. The analysis of crop simulation results allow the researcher to focus on the yield reducing factors and provide better recommendations to produces.

Decision Support System for Agrotechnology Transfer DSSSAT 9.0 (Hoogenboom et al., 2010; Jones et al., 2003) which includes the Cropping System

Model (CSM)-CERES-Wheat, is a comprehensive decision support system for assessing management options. The CSM-CERES-Wheat model, operating on a daily time step from planting to maturity, allows simulation of growth, development and yield under a variety of weather, soil conditions, management practices and environmental conditions throughout the world (Bannayan et al., 2003; Nain et al., 2004; Barbieri et al., 2008; Langensiepen et al., 2008; Xiong et al., 2008; Persson et al., 2010; Soler et. al., 2007). In the southeastern United States the CSM-CERES-Wheat model has been used to evaluate wheat grain and straw potential production as an alternative to fossil fuels as an energy source for Alabama and Georgia (Persson et al., 2010). Garcia and Garcia et al. (2008) evaluated the impact of generated weather variables on rainfed and irrigated cotton, maize and peanut through the use of the CSM-CROPGRO-Cotton, CSM-CERES-Maize, CSM-CROGRO-Peanut models for several counties in Georgia. The CSM-CROPGRO-Cotton model has been used to evaluate the effects of shading on cotton when planted in a pecan alley system in southern Georgia (Zamora et al., 2009). The CSM-CROGRO-Peanut model has been used to evaluate irrigation practices for peanuts grown in Georgia (Paz et al., 2007). The objectives of this present study were to (i) to evaluate the performance of the CSM-CERES-Wheat model for simulating growth, development and yield of three winter wheat varieties with different maturity levels growing a three different locations in Alabama and (ii) to analyze the effect of ENSO phase on yield of three wheat varieties planted at four different times at three locations in Alabama using the CSM-CERES-Wheat model.

Materials and Methods

Experimental Data

A field experiment was conducted at the Tennessee Valley Research and Extension Center in Belle Mina, AL (34°41'22.24"N, 86°53'10.66"W), E. V. Smith Research Center in Shorter, AL (32°25'20.46"N, 85°53'20.76"W), and Wiregrass Research and Extension Center in Headland, AL (31°22'39.97"N, 85°18'51.74"W) during the 2009/2010 and 2010/2011 growing seasons. The soil types differed among locations as Belle Mina, AL had a Decatur silty loam, Headland, AL had a Lucy sandy loam, and Shorter, AL had Compass loamy sand. The experiment was conducted in a randomized complete block design with a split-plot restriction on randomization and five replications. Four planting dates at approximately 15 day intervals were assigned to main plots (Table 9) and three wheat varieties with differences in maturity (early, medium and late) were randomized among subplots within each main plot. Subplots were 3.7 m wide by 9.1 m long. The three wheat varieties used for this study were AGS 2060 (early maturing), AGS 2035 (medium maturing), and Baldwin (late maturing). In both years, seeding rate were 377 seeds per square meter. For all locations, the row width was 17.8 cm, using 66 seeds per meter row. All plots received a basal application of nitrogen twice through the growing season: 22.4 kg ha^{-1} at planting and the second application of 112 kg ha^{-1} at the Feekes 4 growing stage. Weeds, insects, and disease were chemically controlled as needed.

Plant, Soil, and Weather Data

Crop phenology such as the number of days until seed emergence, anthesis, and physiological maturity were recorded. The number of leaves, tillers per area, and leaf area index (LAI) were collected throughout the growing season. Biomass was collected at random within each plot from an area of 5 rows by 1 m length three times during the growing season at various phenologic stages (three leaf stage, fifty percent flowering - soft dough, and harvest). The samples were separated into leaves, stems and spikes and were dried at 70^0C for at least 72 h. Yield components such as seed mass and the number of grains per spike were obtained from manually threshing of mature spikes. The number of grains per area obtained from all the grain present in the spike biomass collected at harvest. The number of grains per spike value resulted from dividing the total number of seeds by the total number of heads in each biomass sample. The average seed mass was obtained by dividing the total dry grain weight over total number of grains on the sample.

Soil profile data for the study locations were obtained from the Natural Resources Conservation Service (NRCS), Soil survey division. Soil physical and chemical properties for Decatur silty loam, Lucy sandy loam, and Compass loamy sand soil types were input into the model and used for model simulations (Table 2). At each of the study locations, soil volumetric water content ($cm^3\ cm^{-3}$) was measured at a depth of 25 cm every 4 hours throughout the growing season using the EC-5 soil moisture sensors (Decagon Devices Inc., USA). The soil moisture data was used to calibrate the model's soil- water holding characteristics.

Daily weather data of minimum and maximum air temperature, and total rainfall (mm) for the two field study years (2009-2011) at each study location were obtained from the Cooperative Observer Program (COOPS) of the National weather service. Solar radiation ($MJ\ m^{-2}\ day^{-1}$) was estimated by the WGENR generator (Hodges et al., 1985) and adjusted to represent the south-eastern USA (Garcia y Garcia and Hoogenboom, 2005). Weather input data representing 60 growing seasons (1950 to 2010) was used for the seasonal analysis to assess the differences in management practices (planting date and variety) by ENSO phase.

Model Calibration

Data collected from the field experiment was used to calibrate the CSM-CERES-Wheat model and to generate phenology and growth coefficients for the three varieties included in this study. The model was calibrated with the data collected from the 2009/2010 and 2010/2011 growing seasons at each location. This calibration helped ensure that the constants and response functions were correct and that simulations of growth and yield under specific environmental conditions performed well (Hunt and Boote, 1998)

Soil-Water Holding Characteristics

Because soil moisture was measured at a depth of 25 cm, the volumetric soil water was calibrated for the conditions of soil layers 15 to 30 cm. However, changes to soil properties on the layer 0-15 cm were also necessary. The soil water holding characteristics that are required by the model for each soil horizon include permanent wilting point or lower limit of plant extractable soil water (LL, cm3 cm-3), field capacity or drained upper limit (DUL, cm3 cm^{-}3), saturated water content (SAT, cm3 cm-3), saturated hydraulic conductivity (KSAT, cm h^{-}1), and a soil root growth factor (SRGF). These properties were initially estimated with the SBuild program of DSSAT Version 4.0 (Hoogenboom et al., 2004). The soil water characteristics were then calibrated for the top two soil horizons by adjusting two of the water holding characteristics (LL and DUL) in order to match the simulated values to the observed values for the purpose of making the simulations more specific to the conditions of the field. The values of soil drainage, soil albedo, and runoff curve number were calculated with the SBuild program using data of soil color and drainage, slope, and potential runoff for the soil of each experimental site. The soil parameters selected were those that minimized the root mean square error (RMSE) between simulated and observed volumetric soil water content for each soil depth. Detailed descriptions of the soil physical properties used by the soil water balance submodel in the CSM-CERES-Wheat are presented in Table 9.

Cultivar Coefficients

The CERES-Wheat model requires genetic coefficients that describe the crop life cycle, vegetative growth traits and reproductive traits to simulate performance differences among cultivars (Boote et al, 1996). Seven variety coefficients were generated for each of the AGS 2060 (Early Maturity), AGS 2035 (Medium Maturity), and Baldwin (Late Maturity) wheat varieties. Data for number of days to anthesis and maturity, as well as biomass collected during the growing season (flowering and harvest), number of grains per area, grain number per spike, tillers per area, yield components, and total yield were used to generate the coefficients for each variety. The variety coefficients were obtained in a sequential order following an iterative process starting with the phenologic parameters related to anthesis and maturity, followed by the parameters relating vegetative growth followed by reproductive growth such as grain filling rate and the grain number per spike (Hunt et al., 1993; Hunt and Boote, 1998). An iterative process (Hunt and Boote, 1998) was used to select optimum values for both the phenologic growth parameters and yield parameters. When calibrating the biomass accumulation and wheat yield, a modification of the soil fertility factor (SLPF) was considered as this factor affects the crop growth rate by modifying the daily canopy photosynthetic rate. Model calibration of variety coefficients was conducted after the calibration of the soil water holding characteristics. A detailed description of the variety coefficients used in the simulations by the CSM-CERES-Wheat model is presented in Table 10.

Model Evaluation and Statistical Methods for Performance Assessment

For calibration and evaluation, a comparison of the simulated dates of emergence, anthesis, and maturity as well as simulated values of vegetative biomass (leaves plus steam), above ground biomass, yield and yield components were compared with the observed values for each wheat variety and each one of the four planting dates at each of the three locations included in the field experiment. Independent data for model evaluation was obtained from the Alabama Performance Comparison of Small Grain Varieties Trials conducted at Belle Mina, Headland, and Shorter, AL, during the 2008/2009 growing season and Fairhope, AL, during 2009/2010, and 2010/2011 growing seasons. The Alabama Performance Comparison of Small Grain Varieties Trials included the three wheat varieties planted within the window of the second planting date of the field study. The model's accuracy was evaluated using three statistical indexes: root mean square error (RMSE), which is the difference between the observed and the predicted values, percentage prediction deviation (PD) and the Willmott (1981) index of agreement (*d*-statistic). The values of RMSE, PD and *d*-statistic were computed using equations 1, 2, and 3:

$$RMSE = \left[N^{-1} \sum_{i=1}^{n} \left(P_i - O_i \right) \right]^{0.5} \qquad (1)$$

$$PD(\%) = \left(\frac{P_i - O_i}{O_i} \right) x100 \qquad (2)$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} \left(\left| P_i^{'} \right| + \left| O_i^{'} \right| \right)^2} \right], 0 \leq d \leq 1 \qquad (3)$$

where N is the number of observed values, P_{i} and O_{i} are the predicted and observed values for the ith data values, $P^{'}_{\mathrm{i}} = P_i - \bar{O}$ and $O^{'}_i = O_i - \bar{O}$, and $\bar{O}$ is the mean of the observed values. When evaluating the performance of simulated values, the closer the RMSE to 0, the better the agreement between the simulated and observed values. The *d*-statistic indicates a good fit between simulated and observed values the closer the index values is to one. In relation to PD values, model under predictions can be identified as negative PD values and the opposite for over predictions.

Model Application

Once the model was calibrated and the variety coefficients for the three varieties were identified, a seasonal analysis (Thornton and Hoogenboom, 1994) in DSSAT v. 4.5 was conducted to assess the effect of planting date on three wheat varieties planted at the locations of Belle Mina, Shorter and Headland in Alabama. The seasonal analysis was also used to assess the effect of ENSO phases on yield for the same wheat varieties – planting date – location treatment combinations. Weather data representing 60 growing seasons from 1950 through 2010 was used in the simulation to determine the impact of year-to-year climate variability. The crop management scenarios used for the seasonal analysis were representative of current recommended practices for Alabama. The four planting dates were selected based on a 15 day intervals starting on October 15 for Belle Mina, October 23 for Shorter, and October 29 for Headland. Row spacing was set to 17.8

cm and population was 377 seeds per square meter at planting. Nitrogen, in the form of ammonium nitrate, was broadcast but not incorporated at a rate of 22 kg per hectare at planting and 112 kg per hectare when the crop was at tillering during late February to early March depending on location.

Simulated yield values for the 60 years of weather data for all the treatment combinations were classified by ENSO phase, (e.g., El Niño, La Niña, or Neutral) using the Japan Meteorological Agency (JMA) index. The JMA index is based on a 5 month running mean of sea-surface temperature anomalies. The categorical index is classified based on the October through September, 12 month period, which classifies as a Warm year (El Niño), Cold year (La Niña) or Neutral year based on the running mean anomaly (COAPS, 2009).

Statistical Analysis

An analysis of the effects of planting date and variety selection on winter wheat yield by ENSO phase was conducted. The percentage yield reduction by ENSO phase-planting date combinations for each variety was estimated using equation 4:

$$Y_f = [(Y_z - Y_x)/Y_z]x100 \tag{4}$$

where Y_f is the percent yield reduction, Y_z is the yield of a specific variety for the first planting date and Y_x is the yield of an alternative planting date/ variety. Linear mixed model procedures as implemented in SAS® PROC GLIMMIX were used to analyze the simulated data from the seasonal analysis. Treatment factors, planting date and variety as well as their interactions were considered fixed effects. Location and ENSO phase and their interaction with treatment factors were also considered fixed effects. The residual variation was considered random, which is the appropriate error term for variety and associated interactions. Since there was an *a priori* assumption that interactions should be an important source of variation, the critical *P*-value of 0.10 was used as cutoff. We used the Student Panel option in the GLIMMIX procedure to generate conditional residuals plots, which were then used to investigate the behavior of residuals.

RESULTS AND DISCUSSION

Climatic Analysis

El Niño Southern Oscillation (ENSO) has a strong influence on seasonal and inter-annual changes in precipitation and surface air temperature in the Southeast USA (Stefanova et. al., 2012). For the three study locations in Alabama, the main differences between ENSO phases for the period September through June were related to Precipitation (Figure 8). For Shorter (central-east) and Headland (South-east), AL, the periods between November to March and May to June of El Niño years have higher precipitation than La Niña years. For Belle Mina (north), precipitation during the El Niño phase is higher than the La Niña phase in September, November, December, May and June. When the monthly precipitation deviations for a specific ENSO phase were calculated (deviation is the amount by which the historic average values for a specific ENSO phase differ from the average conditions for all years), higher deviations or excess of precipitation with respect to the historic average values were observed in Headland for El Niño phase compared to Belle Mina for the months of November, January to March and May (data not shown). The opposite occurs during La Niña phase, higher deviations or excess of precipitation respect to the historic average values are observed in Belle Mina compared to Headland for the months of October, November, January, and

February. For Belle Mina, lower precipitation with respect to the historic values and Headland was observed during May and June. Lower average maximum temperature occurred during El Niño years than during La Niña and Neutral years for all three locations (Fig. 8). A comparison of the three locations showed that the Belle Mina location exhibited the lowest average maximum temperature during El Niño years than any other ENSO phases. Neutral years tend to have the lowest average minimum temperature across all locations (Fig. 8). While observing monthly changes in temperature, La Niña years had a tendency to have higher average maximum temperature from October through December throughout all locations, however during January through March lower average minimum and maximum temperature for the Shorter and Headland when compared to El Niño. For the months of March through June, both average minimum and maximum temperature at Shorter and Headland were similar for all the phases of ENSO. At the northern location however, La Niña years tended to have higher average minimum and maximum temperate throughout the entire growing season.

Solar radiation differences between the locations showed that Headland receives the largest amount of solar radiation followed by Belle Mina and Shorter, AL, with the La Niña years exhibiting higher solar radiation than El Niño years. In Belle Mina , there was observed a 9% increase of solar radiation for the month of September, 6% increase for October, 2% increase for February, 5% increase in May and 8% increase during June during the La Niña years compared to the El Niño years. Similar results were observed for Shorter, there was observed a 2% increase of solar radiation for the month of October, 4% increase for November, 2% increase for December, 2% increase for February, 5% increase in May and 3% increase during June. At Headland, there was observed a 1%

increase of solar radiation for the month of October, 4% increase for November, 2% increase for December, 2% increase for February, 5 % increase in May and 3% increase during June during the La Niña years compared El Niño years. Hansen et al. (1998) observed reductions in solar radiation during El Niño years and those were directly related with the increased rainfall and cloud cover during the winter and fall months.

Calibration and Evaluation of the CMS-CERES-Wheat Model Variety Coefficients

The CSM-CERES-Wheat model includes seven coefficients that are specific to each variety, which defines phenology and growth (Table 3). The early maturing variety, AGS 2060, had the lowest value for P1V (days with optimum vernalizing temperature), e.g. 8 days, and also had the lowest value for P1D (reduction in development rate in a photoperiod 10 h shorter than the optimum), e.g., 88.2%. In contrast, the late maturing variety, Baldwin, had the largest value for P1V, e.g., 31 days, and also had the largest value for P1D, e.g., 92.7%, while medium maturing variety, AGS 2035, have P1V and P1D values of 27 days and 89.9%, respectively, which were within the range of AGS 2060 and Baldwin values for the same coefficients. The values for P5 (grain filling duration) were as follows: AGS 2060 - 600°C day, AGS 2035 - 650°C day, and Baldwin - 750°C day. The G1 coefficients (kernel number per unit canopy weight at anthesis) ranged from 23 to 27.8 for the three varieties. The G2 variety (standard kernel size under optimum conditions) accounted for the majority of variation in yield among the varieties with values of 33.6 mg, 42.2 mg, 41.4 mg for the AGS 2060, AGS 2035, and Baldwin varieties, respectively. The value for G3 (standard, non-stressed mature tiller weight including grain) ranged from 1.0 grams for the AGS 2035 variety to 3.1 grams for the

Baldwin variety. The phyllochoron interval (PHINT) ranged from 120°C day for AGS 2060 variety to 131°C day for AGS 2035 variety.

Phenology and Biomass

The evaluation of the CSM-CERES-Wheat model for simulating the number of days between planting and anthesis with data from the 2009/2010 and 2010/2011 showed similarities between the average observed and simulated values for the number of days from planting to anthesis for each of the three varieties across all planting dates at the locations, e.g., 158 observed days and 164 simulated days for AGS 2060 (RMSE = 6 days), 162 observed days and 165 simulated days for AGS 2035 (RMSE = 7.5 days), and 163 observed days and 166 simulated days for Baldwin (RMSE = 8.1 days) (Fig. 9). The coefficient of determination (r^2) between the observed and the simulated duration from planting to anthesis in all three study locations was 0.94, 0.89, and 0.88 for the varieties AGS 2060, AGS 2035, and Baldwin, respectively. The *d* values between the observed and the simulated duration from planting to anthesis at all three study locations were 0.97, 0.96, and 0.96 for the varieties AGS 2060, AGS 2035, and Baldwin, respectively. The RMSE was low for all varieties and the coefficient of determination (r^2) and *d* values were high, which shows the CSM-CERES-Wheat model capacity for simulating the duration of phenology stages. Physiologic maturity was not evaluated because the days to physiologic maturity were not accurately recorded at most of the site-years.

The evaluation of the CSM-CERES-Wheat model for simulating the vegetative biomass with respect to observed data, showed that the best prediction was for AGS

2035 with a *d* value of 0.66, while the Baldwin variety exhibited a *d* value of 0.55(Fig. 10). Overall, the vegetative biomass was fairly well predicted, however, the model over predicted the biomass at all locations for the 2010/2011 growing season. Towards the end of the 2010/2011 growing season, lodging among certain varieties for the early planting dates was observed which could cause a reduction of vegetative growth not accounted for by the model. Overall, RMSE was relatively low for all varieties, AGS 2060 – 2343 kg ha^{-1}, AGS 2035 – 2270 kg ha^{-1}, and Baldwin – 3242 kg ha^{-1} (Fig. 10).

Yield

Simulated average wheat yield across planting dates was under predicted for 13 out of 15 site-year-variety combinations (Table 4). During the 2009/2010 growing season, simulated average yield across planting dates was more accurately predicted, with the lowest PD and RMSE values. Overall, simulated yields for Baldwin, the late maturing variety, were consistently the most accurate among the other varieties and locations. In 3 out of 5 cases, Baldwin had the lowest RMSE and PD, while maintaining high *d* values. For the other two cases occurring in Headland during the seasons 2009/2010 and 2010/2011, Baldwin exhibited the highest lowest RMSE and PD values. When the simulated yield was compared across varieties, locations and years, better model predictions were observed for the 2010/2011 growing season.

An analysis of simulated and observed yield values by location × planting date interaction indicated that the RMSE ranged from 711 kg ha^{-1} (Baldwin planted at Belle Mina) to 1174 kg ha^{-1} (Baldwin planted at Headland) (Fig. 11). During the 2009/2010 growing season at Belle Mina (Fig 11a-c), simulated average yield for Baldwin, the late maturing variety, was more accurate than for the AGS 2060 and AGS 2035 varieties. At the Shorter location during both the 2009/2010 and 2010/2011 growing seasons, Baldwin, the late maturing variety exhibited the highest prediction accuracy compared to the other two varieties, lowest RMSE and highest *d* value. At Headland in contrast, AGS 2060, the early maturing variety, showed the highest yield simulation accuracy but for the 2010/2011 growing season, higher accuracy was observed for the AGS 2035 variety. Independently of the variety, the lowest model yield predictions were observed at Headland, with the largest RMSE and lowest *d* values. Figure 11 showed that the highest simulated yield predictions by variety-planting date combinations were obtained for the Belle Mina and Shorter which have the lowest RMSE values, and high coefficient of determination (r^2) and *d*- statistic values (Table 12 and Fig. 11).

Following calibration, the CSM-CERES-Wheat model was evaluated for simulating grain yield of the same three wheat varieties planted in the Alabama Performance Comparison of Small Grain Varieties Trials conducted at various site-years. The data revealed similar observed and predicted yield for each of the three varieties planted at the Belle Mina, Shorter, Headland, and Fairhope locations (Table 13). During the 2008/2009 growing season, the lowest prediction accuracy was observed at Belle Mina (Baldwin variety – PD of -37.80) and the highest prediction was for Shorter (Baldwin variety – PD of -1.60). Across locations, the highest prediction accuracy was observed for the AGS 2035 variety, lowest RMSE and PD values combined (Table 13). The lack of accuracy at the Belle Mina location in 2008/2009 could be explained by the wheat lodging at harvest which was not accounted for by the model. In 4 out of 5 location-variety combinations, the model under predicted the simulated yield for AGS 2060, while over predicted the yield for the AGS 2035 variety. Across locations and years, the yield for Baldwin was over predicted in a higher number of cases compared to the other two varieties. The overall model evaluation showed low RMSE and PD values for most year-location-variety combinations. The range of RMSE was 170 kg/ha to 2814 kg/ha and PD ranged from -1.60% to 18.77% (Table 13).

Model Application: Case I - Evaluation of Optimum Planting Dates and Varieties per Location

Model calibration and evaluation results showed good agreement between the observed and simulated yield values for the three varieties planted at three locations, therefore, the CSM-CERES-Wheat model was used to evaluate the impact of planting date and variety selection on wheat yield at various locations in Alabama. Model simulations for various location-variety-planting date combinations using 60 years of historic weather data showed that the average yield decreased as planting was delayed specially for the Belle Mina and Headland locations (Fig. 12). When simulated yield across all varieties for the current farmers' planting date (PD2) was compared to the last planting date (PD4), yield reductions of 19% for Belle Mina and 12% for Headland were observed. Simulations showed that planting wheat 15 days earlier (PD1) than the farmers' planting date (PD2) could result in yield increases of 6% for Belle Mina and 3% for Headland. In contrast, the impact of planting date on yield was not as evident at the Shorter location compared to the Belle Mina and Headland locations, in fact late planting dates (PD4) might result in a 7% yield increase respect to the farmers' planting date (PD2) (Fig. 12). The percentage yield reduction associated with planting dates did vary by variety. For the Baldwin variety, the percent yield reduction between the early and late planting dates (PD1 vs. PD4) at Belle Mina was much higher (24%) than Headland (14%). Similar results were observed for the AGS 2035 and AGS 2060 varieties with yield reductions in Belle Mina of 26% and 20%, respectively. Yield reductions associated with late plantings at Headland were not as severe as in Belle Mina, ranging from 16% for AGS 2035 and 14% for AGS 2060. The yield differences between varieties for various planting date-location combinations could be explained by a possible interaction between the variety's vernalization requirements and the climatic conditions at each study location. Baldwin variety has long vernalization requirements compared to AGS 2035 and AGS 2060, therefore, delayed planting might cause vernalization requirements not to be met due to differences in heat unit accumulation (Table 11 and Table 14).

Simulated average yield across planting dates indicated that the AGS 2035 and Baldwin varieties, medium and late maturity varieties respectively, out-yielded the early maturing variety, AGS 2060, at all locations but especially in Belle Mina and Headland where significant yield differences between those varieties and the AGS 2060 were observed (location × variety interaction, $P < 0.0001$) (Table 14). The late maturating variety, Baldwin, tended to have the highest yield when compared to the early, AGS 2060, or medium, AGS 2035, maturing variety across planting dates and locations. At Belle Mina, Baldwin out-yielded the early maturing variety, AGS 2060, by an average of 1671 kg ha^{-1} and the medium maturing variety, AGS 2035, by 188 kg ha^{-1}, respectively (Table 14). No significant differences among the varieties were observed at Shorter, however, the late maturating variety exhibited the highest yield. At Headland, significant yield differences among the varieties were observed with yield increases of 1010 kg ha^{-1}

and 277 kg ha^{-1} for Baldwin compared to AGS 2060 and AGS 2035, respectively (Table 14).

Model Application: Case II - Evaluation of Optimum Planting Dates and Variety for Various ENSO Phase-Location Combinations

The analysis of variance for simulated wheat yield data indicated differences in the main effects of ENSO phase, location, planting date and, variety accounting for 83% of the total treatment variation. When the interactions of ENSO phase × Location, Location × Variety and Location × Planting date were added to the model, 98% of the total variation was accounted indicating the need for further analysis based on mixed models methodology.

An interaction between ENSO phase × Location ($P < 0.0001$) was observed from the simulated wheat yield using 60 years of historic weather data (Table 15, Fig. 13). During the La Niña, the highest simulated wheat yield was observed compared to the other ENSO phases across all locations (Table 15). In contrast, the lowest yield was observed for El Niño phase at Belle Mina and Headland with yield reductions of 12.5% and 16% respectively when compared to the La Niña phase (Table 15). At Shorter, a yield reduction of 1.6% during El Niño years with respect to La Niña years was calculated. The yield variations between ENSO phases could be associated with seasonal and inter-annual climate variability especially the amount and distribution of precipitation. During the La Niña years, there is a higher amount of solar radiation than during the El Niño years, which contribute to an increase in the amount of photosynthates available for spike growth (Fisher, 1985) (Fig. 8, Table 16). In contrast, there is a tendency for higher precipitation during the El Niño years than during the La Niña years, however the amount of precipitation increase changed by location (Fig. 8). During the spring months of March, April and May, the period in which anthesis and grain filling occurs, environmental stress especially reductions in water and nitrogen might impact yield (Wuest and Cassman, 1992); hence, for Belle Mina and Shorter, there risk for these stresses during the El Niño years might be higher because of the lower total observed precipitation, while at Headland, the greater risk might occur during La Niña years (Table 16). The findings from Rasmussen et al. (1998) on the equal importance of precipitation distribution and total precipitation might explain the high yield at Belle Mina and Shorter during the La Niña years and Headland during El Niño years when precipitation was distributed during the spring months (Table 16).

The evaluation of the differences in wheat yield by ENSO phase and planting date for Belle Mina showed that for all varieties, the early planting date resulted in the highest yield with yield decreasing as planting was delayed (PD1 > PD2 > PD3 > PD4) (Fig. 13). The risk for yield losses associated with delayed planting was higher during El Niño than the other ENSO phases, especially for the early maturing variety (Table 17, Fig. 13). In contrast, during La Niña and Neutral phases, early maturing variety exhibited the lowest yield reduction associated to late planting compared with the AGS 2035 and Baldwin varieties (Table 17). The simulated results from Belle Mina were consistent with the findings of Ferrise et al. (2010), who reported a high correlation between higher yield and longer vegetative periods with greater precipitation events for early plantings compared to late winter plantings.

At Shorter, there was not a clear trend for higher yield associated to a specific ENSO phase. The simulated average yield for the medium and late maturing varieties, AGS 2036 and Baldwin varieties, tended to be higher for later planting dates independent of the ENSO phase (Fig. 13). In contrast, for the early maturing variety, AGS 2060, there was no yield variation between planting dates across ENSO phases. The later planting dates result on later anthesis, which might result on optimization of grain filling due to more precipitation events occurred in late May during La Niña and Neutral years.

At Headland, La Niña years tend to result in higher simulated yield averages than El Niño years and not many differences with Neutral years. Independently of the ENSO phase, the first planting date resulted in the highest yield across all varieties (Fig. 13). Overall, the simulated yield for all varieties decreased as planting was delayed, except for AGS 2060 during the Neutral years with yield following the pattern of PD2> PD1 > PD3 > PD4. At Headland, the impact of late planting on wheat yield was not as pronounced as in Belle Mina even though this site is characterized by elevated ambient temperatures, less fluctuation of ambient air temperature, and less precipitation at all growth stages when compared to the other locations (Fig. 8 and Table 16). When simulated yield from the earliest planting date (PD1) was compared to the late planting date (PD4), higher percentage yield reduction was observed during the Neutral years followed by La Niña years. Independent of the ENSO phase, the AGS 2035 exhibited the highest yield reduction as a result of delayed planting (Table 17). During the El Niño years, AGS 2060, the early maturing variety, exhibited the highest yield reduction (16.9%), followed by AGS 2035 (16.25%) and Baldwin (12.8%) (Table 17). During the La Niña years, there was not a broad range of yield reduction differences between the varieties, however the AGS 2060 had the lowest yield reduction (10.45%) followed by Baldwin (11.89%) and AGS 2035 (12.32%). Neutral years exhibited a broad range of yield reduction differences between the locations and varieties. For Belle Mina, the AGS 2060 had the lowest yield reduction (18.89%) followed by Baldwin (24.17%) and AGS 2035 (25.44%). Similarly, at Headland, the AGS 2060 had the lowest yield reduction (14.94%) followed by Baldwin (16.26%) and AGS 2035 (18.45%). The simulated yield results for Belle Mina and Headland were consistent with the findings from Bassu et al. (2009) and Subedi et al. (2007), who observed that earlier planting dates increased wheat grain yield in the Mediterranean and Canadian environments and also the results presented by Ferrise et al. (2010) and Gomez-Macpherson and Richards (1995), who observed grain yield reductions as a result of delayed planting.

Conclusions

The CSM-CERES-Wheat model was able to accurately simulate phenology and yield for the three varieties of winter wheat grown at three locations in Alabama. Vegetative biomass was reasonably simulated, especially for the AGS 2035 variety. For the Belle Mina and Headland, average yield decreased as planting date was delayed with the medium maturing variety (AGS 2035) having higher yield than the early or late maturing variety during the 2009/2010 and 2010/2011 growing seasons. Based on the results from the seasonal analysis, yield losses, especially at Belle Mina and Headland, could be expected from delaying planting date beyond the farmers' customary planting date. In contrast, at Shorter, delayed planting might result in yield increases as a consequence of a favorable precipitation distribution and accumulation during late May of La Niña and Neutral years. In addition, planting a late maturing variety, (e.g., Baldwin) throughout north to south locations Alabama might result on higher yield than other varieties if delayed planting is avoided.

This study also showed that the CSM-CERES-Wheat model can help develop a methodology for the application of seasonal analysis forecasting to agricultural management for the purpose of reducing the risk of production associated with climate variability caused by ENSO. During the La Niña years, the highest simulated wheat yield was observed compared to the other ENSO phases across all locations (Table 7). Overall, the simulated yield for all varieties decreased as planting was delayed at Headland and Belle Mina. Since the increase in reliable ENSO predictions through several forecasting centers creates the possibility of using climate forecasting to identify management practices for winter wheat production that reduces agricultural risk associated with climate in Alabama and other ENSO affected regions.

Referances

Adams R.M., K.J. Bryant, B.A. McCarl, D.M. Legler, J. O'Brien, A. Solow, R. Weiher. 1995. The value of improved long range weather information. Contemporary Economic Policy 13:10–19.

Asseng, S., P.C. McIntosh, G. Wang, and N. Khimashia. 2011. Optimal N fertilizer management based on a seasonal forecast. European J. Agron. 38:66-73.

Baker, C.K., J.N. Gallagher, J.L. Monteith. 1980. Daylenght and leaf appearance in winter wheat. Plant Cell Environ. 3:285-287

Bakker, M.M., Govers. G., Ewert, F. Rounsevell, M., and R. Jones. 2005. Variability in regional wheat yields as a function of climate, soil and economic variables: Assessing the risk of confounding. Agric. Ecosys. Environ.110:195–209.

Bannayan, M., N.M.J. Crout, and G. Hoogenboom. 2003. Application of the Ceres-Wheat model for within season prediction of winter wheat in the United Kingdom. Agron. J. 95:114-125.

Barbieri, P., H.S. Rozas and H.E. Echeverria. 2008. Time of nitrogen application affects nitrogen use efficiency of wheat in the humid pampas of Argentina. Can. J. of Plant Sci. 88:849-857.

Bauer, A., A.B. Frank, A.L. Black. 1984 Estimation of spring wheat leaf growth rates and anthesis from air temperature. Agron. J. 76:829-835

Bassu, S. Asseng, R. Motzo, F. Giunta.2009. Optimizing sowing date of durum wheat in a variable Mediterranean environment. Field Crops Res. 111:109–118.

Brooking, I.R. 1996. Temperature Response of Vernalization in Wheat: A Developmental Analysis. Ann. Bot. 78: 507-512.

Boote, K.J., J.W. Jones, and N.B. Pickering. 1996. Potential uses and limitations of crop models. Agron. J. 88:704-716

Boyer, J. S. 1982. Plant productivity and environment. *Science* 4571: 443 – 448

Center for Ocean-Atmospheric Prediction Studies (COAPS). 2009. ENSO Index According to JMA SSTA. http://coaps.fsu.edu/jma.shtml. Accessed April 6, 2012.

Chen, C., W.A. Payne, R.W. Smiley, M.A. Stoltz. 2002. Yield and water-use efficiency of eight wheat varieties planted on seven date in northeastern Organ. Agron. J. 95:836843.

Cusack, D.F. 1983. Introduction: reviving the Green Revolution. In: Cusack, D.F. (Ed.). Agroclimate Information for Development: Reviving the Green Revolution. Westview Press. Boulder, CO, USA. pp. xii-xvi.

Delécolle,R., F. Couveur, P. Plunchard, C. Varlet-Grancher. 1985. About the leaf-daylenght model under French conditions. W. Day and R.K. Atlin (ed.) Wheat growth and modeling. Phenum Press, New York p.25-31

Ferrise, R, A. Triossi, P. Strantonovitch, M. Bindi, and P. Martre. 2010. Sowing date and nitrogen fertilization effects on dry matter and nitrogen dynamics for durum wheat: An experimental and simulation study. Field Crops Res. 117:245-257.

Fisher, R.A. 1985. Number of kernels in wheat crops and the influence of solar radiation and temperature. J. of Agric. Sci. 105:447-461.

Garcia Y Garcia, A., and G. Hoogenboom. 2005. Evaluation of an improved daily solar radiation generator for the southeastern USA. Climate Res.29, 91-102.

Garcia Y Garcia, A., L.C. Guerra and G. Hoogenboom. 2008. Impact of generated solar radiation on simulated crop growth and yield. Ecological Modeling 210:312-326.

Garnett, E. R., M. L. Khandekar, 1992: The impact of large-scale atmospheric circulations and anomalies on Indian monsoon droughts and floods and on world grain yields—A statistical analysis. Agric. For. Meteor., 61, 113–128.

Griffiths F.E., R.F. Lyndon, and M.D. Bennett. 1985. The effects of vernalization on the growth of the wheat shoot apex. Ann. Bot. 56: 501-511.

Gomez-Macpherson, H.G. and R.A. Richards. 1995. Effect of sowing time on yield and agronomic characteristics of wheat in southeastern Australia. Aust. J. Agric. Res. 46: 1381-1399.

Gott M.B., F.G. Gregory, and O.N. Purvis. 1955**.** Studies in vernalization of cereals XIII. Photoperiodic control of stages in flowering between initiation and ear formation in vernalized and unvernalized `Petkus' rye. Ann . Bot. 19: 87-126.

Hanson, K., G.A. Maul. 1991. Florida precipitation and the Pacific El Nino, 1985-1989. Florida Scientist 54: 160-168.

Hansen J.W., A. Hodges, J.W. Jones. 1998. ENSO influences on agriculture in the southeastern United States. J Clim. 11:404–411.

Hansen J.W., J.W. Jones, A. Irmak, F. Royce. 2001. El Niño–Southern Oscillation impacts on crop production in the Southeast United States. In: Hatfield JL, Volenec JJ, Dick WA, Kral DM. (eds) Impacts of El Niño and climate variability on agriculture. ASA Special Publication no. 63. Madison, WI.

Hayman, P.T., A.M. Whitbread and D.L. Gobbett. 2010. The impact of El Niño Southern Oscillation on seasonal drought in the southern Australian grainbelt. Crop and Pasture Sci. 61:528-539.

Hildebrand, P., A. Caudle, V. Cabrera, M. Downs, M. Langholtz, A. Mugisha, R. Sandals, A. Shrair, and K. Beach. 1999. Potential Use of Long-Range Climate Forecasts by Agricultural Extension Agents in Florida: A Sondeo Report, Staff Paper SP 99-9. Food and Resource Economics Depatrment, University of Florida. pp25.

Hoogenboom, G., J. W. Jones, P. W. Wilkens, C. H. Porter, W. D. Batchelor, L. A. Hunt, K. J. Boote, U. Singh, O. Uryasev, W. T. Bowen, A. J. Gijsman, A. S. Du Toit, J. W. White, and G. Y. Tsuji. 2004. Decision Support System for Agrotechnology Transfer. Ver. 4.0. Honolulu, Hawaii: University of Hawaii

Hoogenboom, G., J.W. Jones, P.W. Wilkens, C.H. Porter, K.J. Boote, L.A. Hunt, U. Singh, J.L. Lizaso, J.W. White, O. Uryasev, F.S. Royce, R. Ogoshi, A.J. Gijsman, and G.Y. Tsuji. 2010. Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5 [CD ROM]. University of Hawaii, Honolulu, Hawaii.

Hodges, T., V., French, and S. K., LeDuc. 1985. Estimating Solar Radiation for Plant Simulation Models. AgRISTARS Technical Report JSC-202239; YM-15-00403. Columbia, MO. NOAA/NESDIS/AISC.

Hunt, L.A., J.W. Jones, G. Hoogenboom, D.C. Goodwin, U. Singh, N. Pickering et al. 1993. Generating input and output file structures for crop simulation models. Codata Publication (in press).

Hunt, L.A., K.J. Boote. 1998. Data for model operation, calibration, and evaluation. In: Hoogenboom, G., J.W. Jones, P.W. Wilkens, C.H. Porter, K.J. Boote, L.A. Hunt, U. Singh, J.L. Lizaso, J.W. White, O. Uryasev, F.S. Royce, R. Ogoshi, A.J. Gijsman, and G.Y. Tsuji. (Eds.), Understanding Options for Agricultural Production. Kluwer Academic Publishers, London, pp.9-19.

Jones, J.W., G. Hoogenboom, C.H. Porter, K.J. Boote, W.D. Batchelor, L.A. Hunt, P.W. Wilkens,U. Singh, A.J. Gijsman, and J.T. Ritchie. 2003. DSSAT Cropping System Model. Eur. J. Agron. 18:235-265.

Kiladis, G.N., H.F. Diaz. 1989. Global climatic anomalies associated with extremes in the southern oscillation. J. Climate 2: 1069-1090.

Langensiepen, M., H. Hanus, P. Schoop, and W. Grasle. 2008. Validating CERES-Wheat under North-German environmental conditions. Agric. Systems 97:34-47.

Levy J, and M.L. Peterson. 1972. Response of spring wheat to vernalization and photoperiod. Crop Sci. 12: 487-490.

Nain, A.S., V.K. Dadhwal, and T.P Singh. 2004. Use of CERES-Wheat model for yield forecast in central Indo-Gangetic Plains of India. J. Agric. Sci. Cambridge 142:59-70.

Nicholls, N. 1985. Towards the prediction of major Australian droughts. J. Climatol 5:553-560

Nicholls, N. 1992. Historical El Niño/Southern Oscillation variability in the Australian region. In: Diaz, H.F. and V. Margraf (Eds.) El Niño, historical and paleoclimatic aspects of the Southern Oscillation. Cambridge University Press, Cambridge, UK, pp.151-174.

Olesen, J., T. Jensen, and J. Petersen. 2000. Sensitivity of field-scale winter wheat production in Denmark to climate variability and climate change. Climate Res. 15: 221-238.

Paz, J.O., C.W. Fraisse, L.U. Hatch, A. Garcia y Garcia. L.C. Guerra, O. Uryasev, J.G. Bellow, J.W. Jones, and G. Hoogenboom. 2007. Development of an ENSO-based irrigation decision support tool for peanut production in the southeastern US. Computers and Electronics in Agric.55:28-35.

Persson, T., A Garcia Y Garcia, J.O. Paz, C.W. Fraisse, and G. Hoogenboom. 2010. Reduction in green house gas emissions due to the use of bio-ethanol from wheat grain and straw produced in the south-eastern USA. J. Agric. Sci. 148:511-527.

Rasmussen, P.E., K. W. T. Goulding, J. R. Brown, P. R. Grace, H. H. Janzen, and M. Körschens. 1998. Long-Term Agroecosystem Experiments: Assessing Agricultural Sustainability and Global Change Science. 282 :893-896.

Ropelewski, C.F., M.S. Halpert. 1986. North American precipitation and temperature patterns associated with the El Niño Southern-Oscillation (ENSO). Mon. Wea. Rev. 114: 2352-2362.

Sah, R.K. 1987. Tropical economies and weather information. In: Fein, J.S., P.L. Stephens (Eds.). Monsoons. John Wiley and Sons, New York, pp. 105-119.

Sittel, M.C. 1994. Marginal Probabilities of the Extremes of ENSO Events for Temperature and Precipitation in the Southeastern United States. Technical Report 94-1. Center for Ocean-Atmospheric Prediction Studies, Florida State Univ., Tallahassee, Fla.

Stefanova, L., V. Misra, J. J. O'Brien, E. P. Chassignet. 2012. Hindcast skill and predictability for precipitation and two-meter air temperature anomalies in global circulation models over the Southeast United States. Clim. Dyn. 38:161–173

Soler, C.M.T., P.C. Sentelhas, and G. Hoogenboom. 2007. Application of the CSM-CERES Maize model for planting date evaluation and yield forecasting for maize grown off-season in a subtropical enviroment. Eur. J. Agron. 27:165-177.

Subedi, K.D., B.L. Ma, A.G. Xue. 2007. Planting date and nitrogen effects on grain yield and protein content of spring wheat. Crop Sci. 47 (2007), pp. 36–44

Thornton P.K, G. Hoogenboom. 1994. A computer program to analyze single – season crop model outputs. Agron. J.87:131-136.

USDA- NRCS Soil survey division. 2011. Official Soil Series descriptions. Available at HTTP://soils.usda.gov/techniqual/classification/osd/index.html. verified on Dec.11.2011.

Wuest, S.B., and K.G. Cassman. 1992. Fertilizer-nitrogen use efficiency of irrigated wheat: I. uptake efficiency of preplantversus late-season applied N. Agron. J. 84:682-688.

Willmott, C.J. 1981. On the validation of models. Phys. Geogr. 2:184-194.

Xiong, W. D. Conway, I. Holman and E. Lin. 2008. Evaluation of Ceres-Wheat simulation of wheat production in China. Agron. J. 100:1720-1728.

Zamora, D.S., S. Jose, J.W. Jones and W.P Cropper. 2009. Modeling cotton production response to shading in a pecan alleycropping system using CROPGRO. Agroforestry Systems 76:432-435.

Table 9. Planting dates for the field experiment a in Belle Mina, Shorter, and Headland, AL, during the 2009/10 and 2010/11 growing seasons.

Year/ Location	Planting Date 1	$2^{\dagger}$	3	4
2009/10				
Belle Mina	Oct. 17	Oct. 29	Nov. 15	Nov. 30
Shorter	Oct. 21	Nov. 8	Nov. 22	Dec. 5
Headland	Nov.2	Nov. 16	Nov. 30	Dec. 11
2010/11				
Belle Mina	Oct. 15	Oct. 30	Nov. 15	Nov. 30
Shorter	Oct. 23	Nov. 6	Nov. 20	Dec. 5
Headland	Oct. 29	Nov. 13	Nov. 26	Dec. 10

† Current recommended planting date for winter wheat in Alabama.

Table 10. Soil properties for the experiment conducted at the three study sites in Alabama.

Location	Soil type	Horizon	Depth	Clay	Silt	Cation Exchange Capacity	Field Capacity	Wilting Point	Saturated Water Content
			cm	----% ----		cmol kg^{-1}	----------cm ^{3}/ cm^3 ----------		
Belle Mina	Decatur	Ap	5	31.1	56.2	18.2	0.31	0.17	0.48
	silty	Bt1	20	36.7	50.2	11.3	0.34	0.20	0.47
	loam	Bt2	46	48.9	43.1	9.1	0.40	0.28	0.46
		Bt3	104	54.1	39.4	11.0	0.44	0.32	0.46
		Bt4	132	56.5	34.6	9.8	0.45	0.33	0.47
		Bt5	152	56.2	33.8	10.6	0.46	0.33	0.47
Shorter	Compass	Ap1	18	3.9	11.9	1.9	0.26	0.05	0.41
	loamy	Ap2	28	6.0	13.4	2.1	0.38	0.07	0.41
	sand	Bt1	58	10.5	16.7	2.2	0.18	0.09	0.40
		Bt2	79	13.0	12.8	2.7	0.19	0.10	0.39
		Btv1	102	14.0	11.3	2.5	0.19	0.11	0.38
		Btv2	122	15.3	10.9	2.2	0.20	0.11	0.38
		Btv3	135	17.4	10.8	2.7	0.21	0.12	0.38
		BC	165	18.9	9.5	3.4	0.21	0.13	0.38
Headland	Lucy	Ap	18	7.7	11.1	1.6	0.16	0.08	0.40
	sandy	EB	58	9.8	13.3	2.0	0.18	0.09	0.39
	loam	Bt1	79	11.2	12.2	2.9	0.18	0.09	0.39
		Bt2	109	24.1	8.3	4.9	0.24	0.15	0.38
		Bt3	157	22.3	8.4	3.7	0.23	0.14	0.38

Table 11. Cultivar specific coefficients (CC) used for simulations with the CSM-CERES-Wheat Model for the winter wheat varieties AGS 2060, AGS 2035, and Baldwin.

CC	Explanation	AGS 2060	AGS 2035	Baldwin
P1V	Days at optimum vernalizing temperature (days)	8.00	27.00	31.00
P1D	Photoperiod response (% reduction in rate/10 h drop in photoperiod)	88.2	89.9	92.7
P5	Grain filling (excluding lag) phase duration (°C day)	600	650	750
G1	Kernel number per unit canopy weight at anthesis (#/grams)	23.0	23.5	27.8
G2	Standard kernel size under optimum conditions (mg)	33.6	42.2	41.4
G3	Standard, non-stressed tiller weight (including grain) (g dry weight)	2.00	1.00	3.10
PHINT	Growing degree days required for a leaf tip to emerge - Phyllochron interval (°C day)	120	131	125

Table 12. Observed and simulated average wheat yield, averaged across planting dates for the three varieties planted at three locations in Alabama.

Location	Variety	Observed kg ha^{-1}	Simulated kg ha^{-1}	PD [†] (%)	RMSE[‡] kg ha^{-1}	r^2 [††]
2009/2010						
Belle Mina	Early - AGS 2060	4740	4158	-12.28	826	0.65
	Medium - AGS2035	6290	5481	-12.86	852	0.94
	Late - Baldwin	6153	5846	-4.99	711	0.87
Shorter	Early - AGS 2060	4365	3375	-22.68	1075	0.63
	Medium - AGS2035	4588	3875	-15.54	1071	0.18
	Late - Baldwin	4457	4134	-7.25	959	0.23
Headland	Early - AGS 2060	4064	3109	-23.50	1110	0.96
	Medium - AGS2035	5241	3958	-24.48	1480	0.14
	Late - Baldwin	5608	4152	-25.96	1519	0.67
2010/2011						
Shorter	Early - AGS 2060	4666	4307	-7.69	396	0.99
	Medium - AGS2035	4862	4477	-7.92	617	0.40
	Late - Baldwin	4592	4332	-5.66	590	0.71
Headland	Early - AGS 2060	3462	3005	-13.20	662	0.59
	Medium - AGS2035	3614	3952	9.35	457	0.91
	Late - Baldwin	3412	3953	15.86	663	0.82

†	Percentage prediction deviation
‡	Root mean squared error
††	Coefficient of determination
‡‡	Willmott Index of Agreement

Table 13. Observed and simulated average wheat yield used for evaluation of the CSM-CERES-Wheat model at various site-years for the three varieties under this study. †

Location	Variety	Observed kg ha^{-1}	Simulated kg ha^{-1}	PD ‡ (%)	RMSE § kg ha^{-1}
2008/2009					
Belle Mina	Early - AGS 2060	4900	5819	-15.79	919
	Medium - AGS2035	4765	7230	-34.09	2465
	Late - Baldwin	4631	7445	-37.80	2814
Shorter	Early - AGS 2060	3765	3020	24.67	745
	Medium - AGS2035	3564	3389	5.16	175
	Late - Baldwin	3496	3553	-1.60	57
Headland	Early - AGS 2060	3833	3663	4.64	170
	Medium - AGS2035	3698	4027	-8.17	329
	Late - Baldwin	3564	4276	-16.65	712
2009/2010					
Fairhope	Early - AGS 2060	3846	3610	6.54	236
	Medium - AGS2035	3638	4092	-11.09	454
	Late - Baldwin	3651	4236	-13.81	585
2010/2011					
Fairhope	Early - AGS 2060	4536	3819	18.77	717
	Medium - AGS2035	4506	4695	-4.03	189
	Late - Baldwin	4494	5056	-11.12	562

† Observed data was coming from the 2008-2011 Alabama Performance Comparison of Small Grain Varieties Trials.

‡ Percentage prediction deviation

§ Root mean squared error

Table 14. Simulated average yield for three wheat varieties planted at Belle Mina, Shorter, and Headland, AL, using 60 years of historic weather data.

				Contrast P-value vs.	
Location	Variety	Mean	Rank‡	Medium	Late
		------ kg ha^{-1} -------			
Belle Mina	Early- AGS 2060	5238	3	<0.0001	<0.0001
	Medium- AGS 2035	6715	2		0.2218
	Late- Baldwin	6903	1		
Shorter	Early- AGS 2060	4224	3	0.4251	0.1772
	Medium- AGS 2035	4366	2		0.8497
	Late- Baldwin	4428	1		
Headland	Early- AGS 2060	3853	3	<0.0001	<0.0001
	Medium- AGS 2035	4586	2		0.0363
	Late- Baldwin	4863	1		

‡ Yield ranked from highest to lowest.

Table 15. Estimated least square means of the simulated winter wheat average yield for three varietires each ENSO phase at the three study site in Alabama. Average yield across all years, planting date, and variety for each of the three locations

		Yield			Contrast *P*-value vs.	
Location	ENSO phase	Mean	SE[†]	Rank[‡]	La Niña	Neutral
		------ kg ha^{-1} --- ----				
Belle Mina	EL Niño	5843	86.55	3	<0.0001	<0.0001
	La Niña	6680	89.59	1		0.0031
	Neutral	6334	60.20	2		
Shorter	EL Niño	4358	86.55	2	0.8421	0.4473
	La Niña	4429	89.59	1		0.1552
	Neutral	4231	60.20	3		
Headland	EL Niño	3972	86.55	3	<0.0001	<0.0001
	La Niña	4730	89.59	1		0.4516
	Neutral	4601	60.20	2		

[†] Standard error

[‡] Yield ranked from highest to lowest.

Table 16. Average solar radiation, precipitation, maximum and minimum temperature of ENSO phase.

Location	ENSO Phase	Growth Stage	Solar Radiation	Maximum Temperature	Minimum Temperature	Precipitation
			MJ $m^{-2}d^{-1}$	°C	°C	mm
Belle Mina	EL Niño	Planting	11.32	19.72	6.80	15.26
		Tillering	11.20	13.78	1.49	13.40
		Heading	18.01	22.59	9.23	12.14
		Harvesting	21.02	28.54	15.90	7.44
	La Niña	Planting	11.87	20.85	7.19	13.56
		Tillering	11.21	13.91	1.71	14.17
		Heading	18.36	22.80	9.33	12.85
		Harvesting	22.43	29.09	15.79	5.83
	Neutral	Planting	11.59	19.86	6.51	14.18
		Tillering	11.01	12.80	0.83	13.09
		Heading	18.03	22.00	8.79	12.49
		Harvesting	21.73	28.69	15.79	7.55
Shorter	EL Niño	Planting	12.33	22.32	9.76	13.03
		Tillering	11.89	17.29	4.84	12.85
		Heading	18.58	24.79	11.96	10.76
		Harvesting	22.38	30.10	18.16	6.80
	La Niña	Planting	12.54	22.95	9.96	12.61
		Tillering	12.09	17.04	4.58	12.14
		Heading	18.76	24.81	11.78	11.68
		Harvesting	22.94	30.30	17.92	6.69
	Neutral	Planting	12.32	22.56	9.85	12.86
		Tillering	11.92	16.62	4.49	13.22
		Heading	18.95	24.51	11.52	11.58
		Harvesting	22.42	30.34	18.17	6.11
Headland	EL Niño	Planting	13.01	22.98	9.94	12.89
		Tillering	12.66	18.05	5.23	12.26
		Heading	18.62	25.46	12.44	11.24
		Harvesting	21.99	30.48	18.06	8.79
	La Niña	Planting	13.01	23.62	9.98	11.88
		Tillering	12.53	17.65	4.90	14.98
		Heading	18.84	25.50	12.21	11.71
		Harvesting	22.73	30.84	17.81	7.54
	Neutral	Planting	12.85	23.14	9.86	12.30
		Tillering	12.59	17.26	4.23	13.70
		Heading	19.35	25.27	11.53	10.64
		Harvesting	22.73	30.81	17.83	6.56

Table 17. Mean yield reduction (%) of three wheat varieties planted at two different times and growing under different ENSO phases. varieties

Location	ENSO phase	Variety	Yield reduction (%)†
Belle Mina	EL Niño	Early - AGS 2060	25.22
		Medium - AGS2035	27.48
		Late - Baldwin	24.50
	La Niña	Early - AGS 2060	18.46
		Medium - AGS2035	24.66
		Late - Baldwin	24.35
	Neutral	Early - AGS 2060	18.89
		Medium - AGS2035	25.44
		Late - Baldwin	24.17
Headland	EL Niño	Early - AGS 2060	16.94
		Medium - AGS2035	16.25
		Late - Baldwin	12.80
	La Niña	Early - AGS 2060	10.45
		Medium - AGS2035	12.32
		Late - Baldwin	11.89
	Neutral	Early - AGS 2060	14.94
		Medium - AGS2035	18.45
		Late - Baldwin	16.26

† The yield reduction was calculated from the yield of wheat planted using planted date 1(PD1) and planting date 4 (PD4)

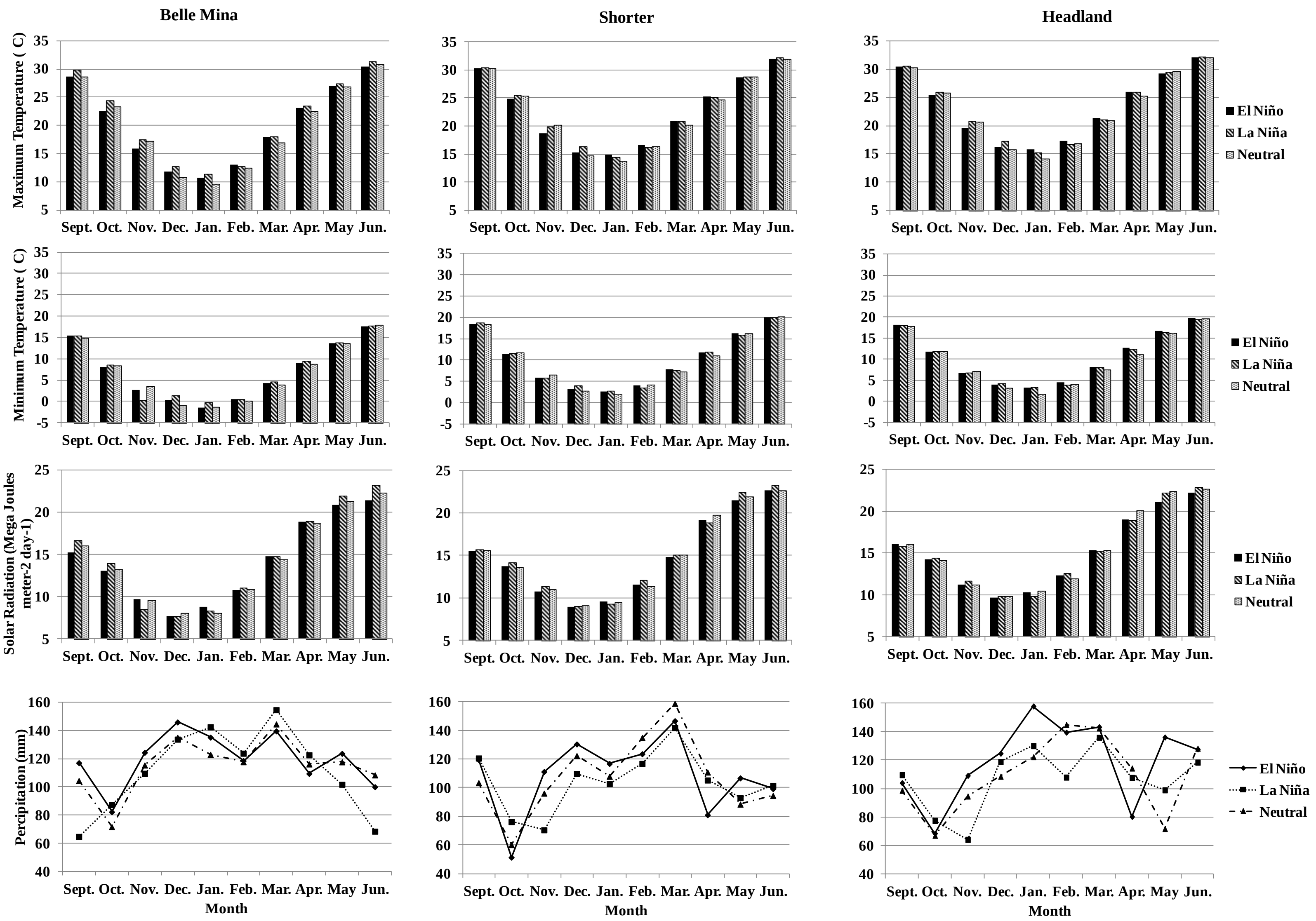

Fig. 8. Historic average maximum temperature, minimum temperature, solar radiation and monthly total precipitation for Belle Mina, Shorter, and Headland in Alabama according to the El Niño Southern Oscillation phases.

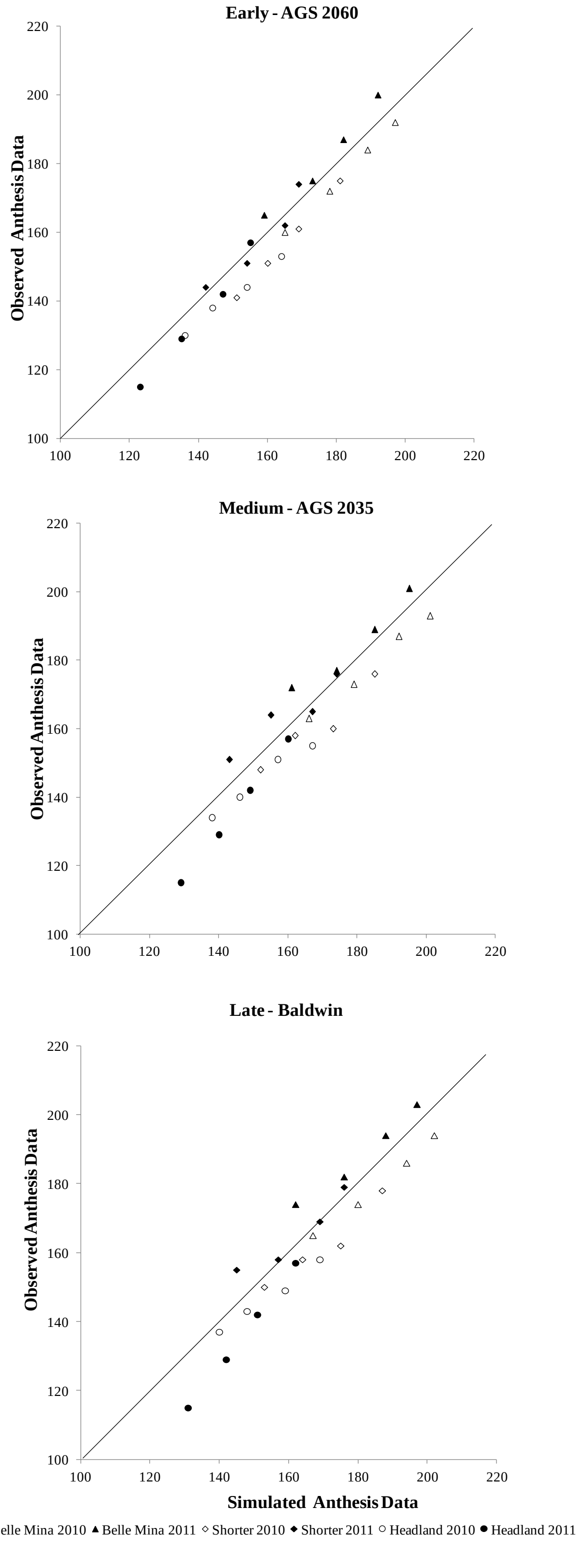

Fig. 9. Observed and simulated anthesis days for three varieties wheat varieties planted at Belle Mina, Shorter, and Headland, AL, during the 2009/2010 and 2010/2011 growing seasons.

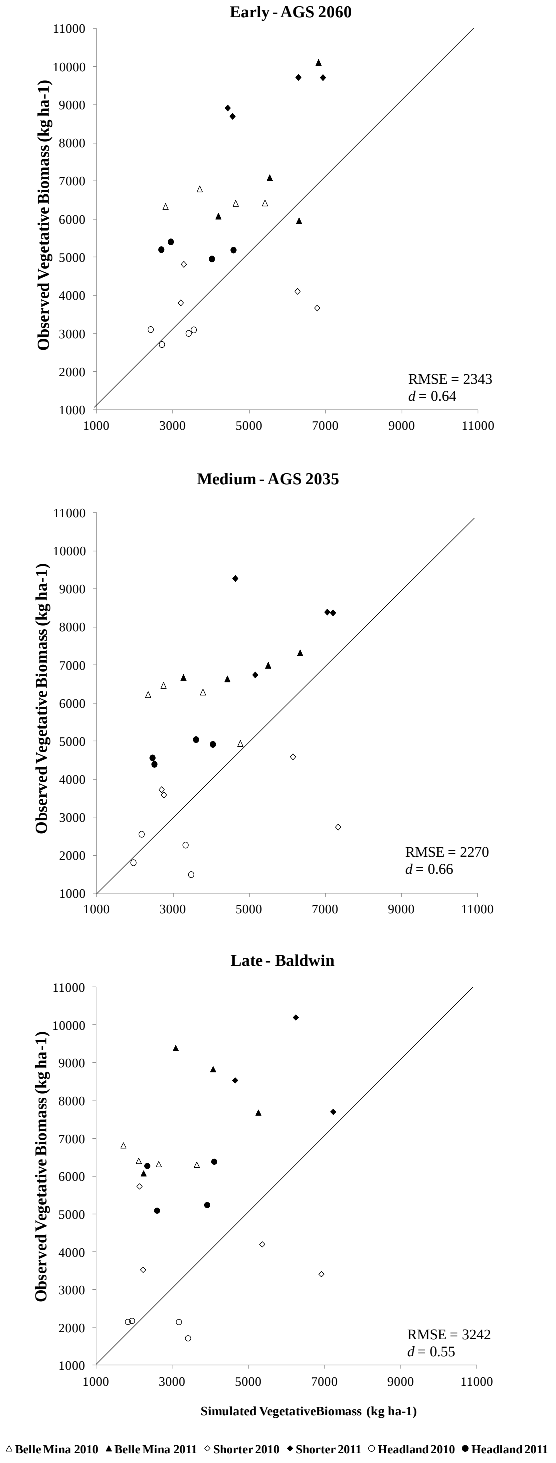

Fig. 10. Observed and simulated vegetative biomass (kg ha^{-1}) for the wheat varieties planted at Belle Mina, Shorter, and Headland, AL, varieties during the 2009/2010 and 2010/2011 growing seasons.

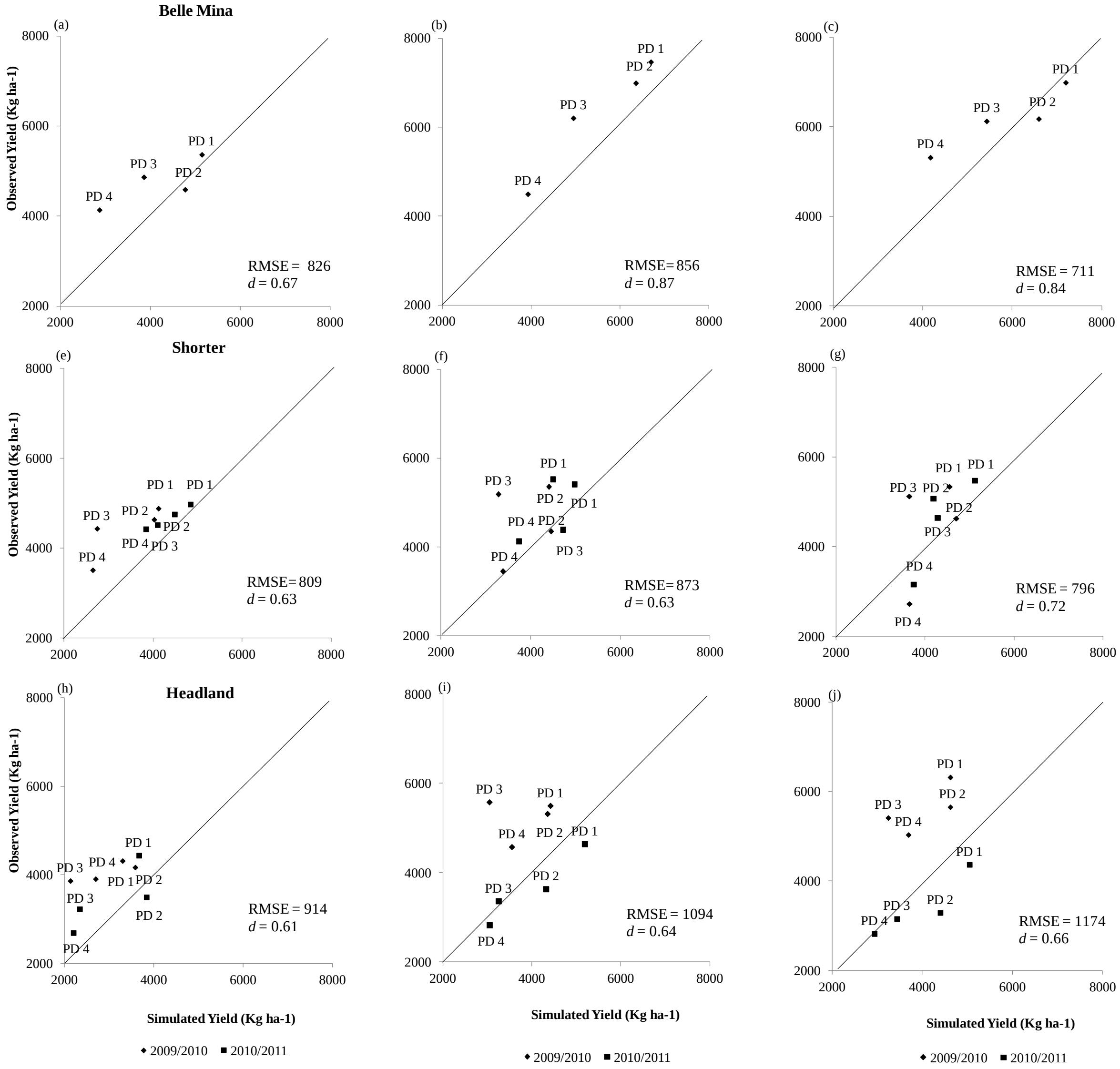

Fig. 11. Observed and simulated yield (kg ha^{-1}) for the wheat varieties AGS 2060 (a, e, h), AGS2035(b, f, i) and Baldwin (c, g, i) planted at four different planting dates at Belle Mina, Shorter, and Headland, AL, during the 2009/2010 and 2010/2011 growing season

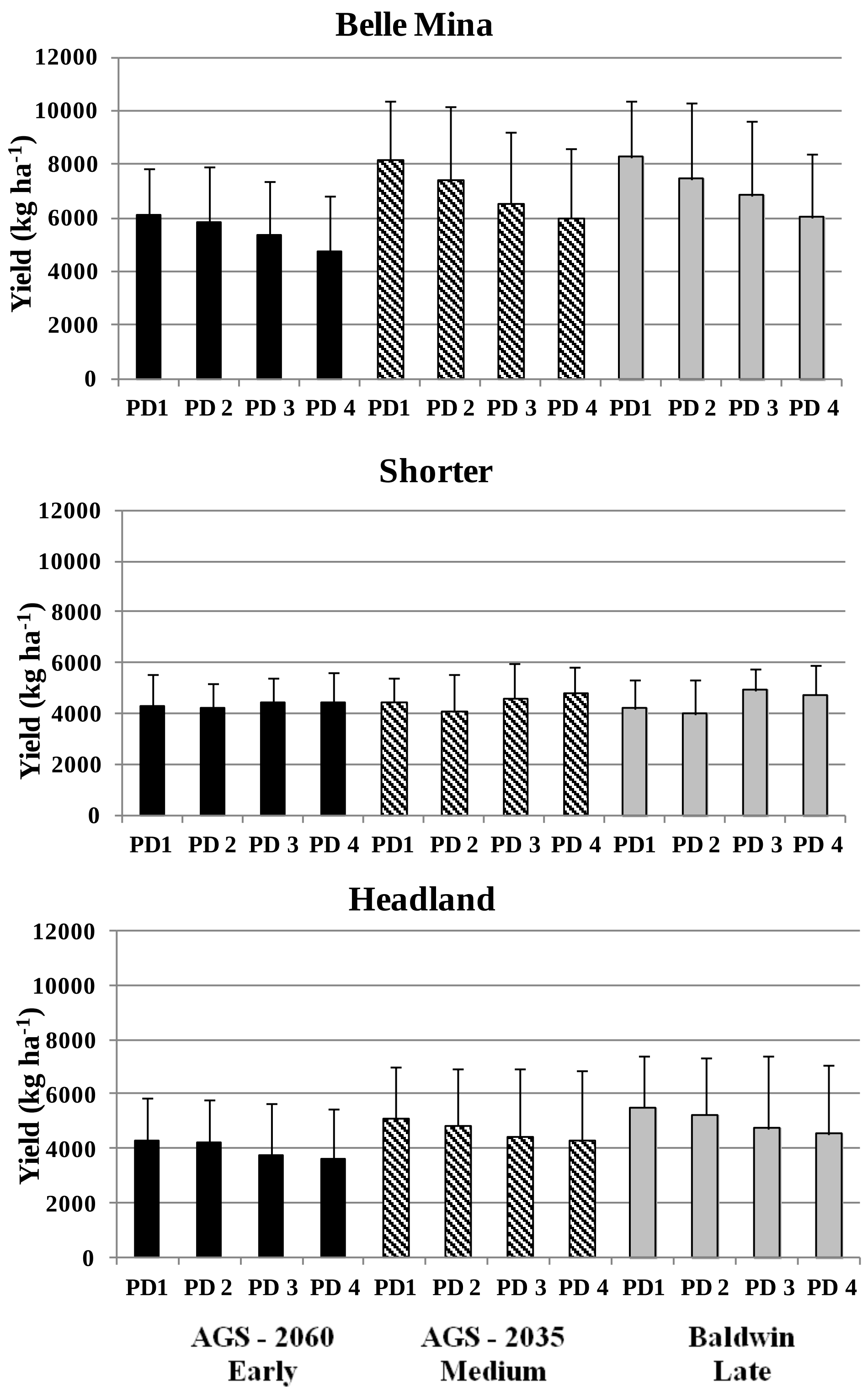

Fig. 12. Simulated average yield by variety and planting date resulted from the seasonal analysis conducted at Belle Mina, Shorter, and Headland, AL, using 60 years of historic weather data

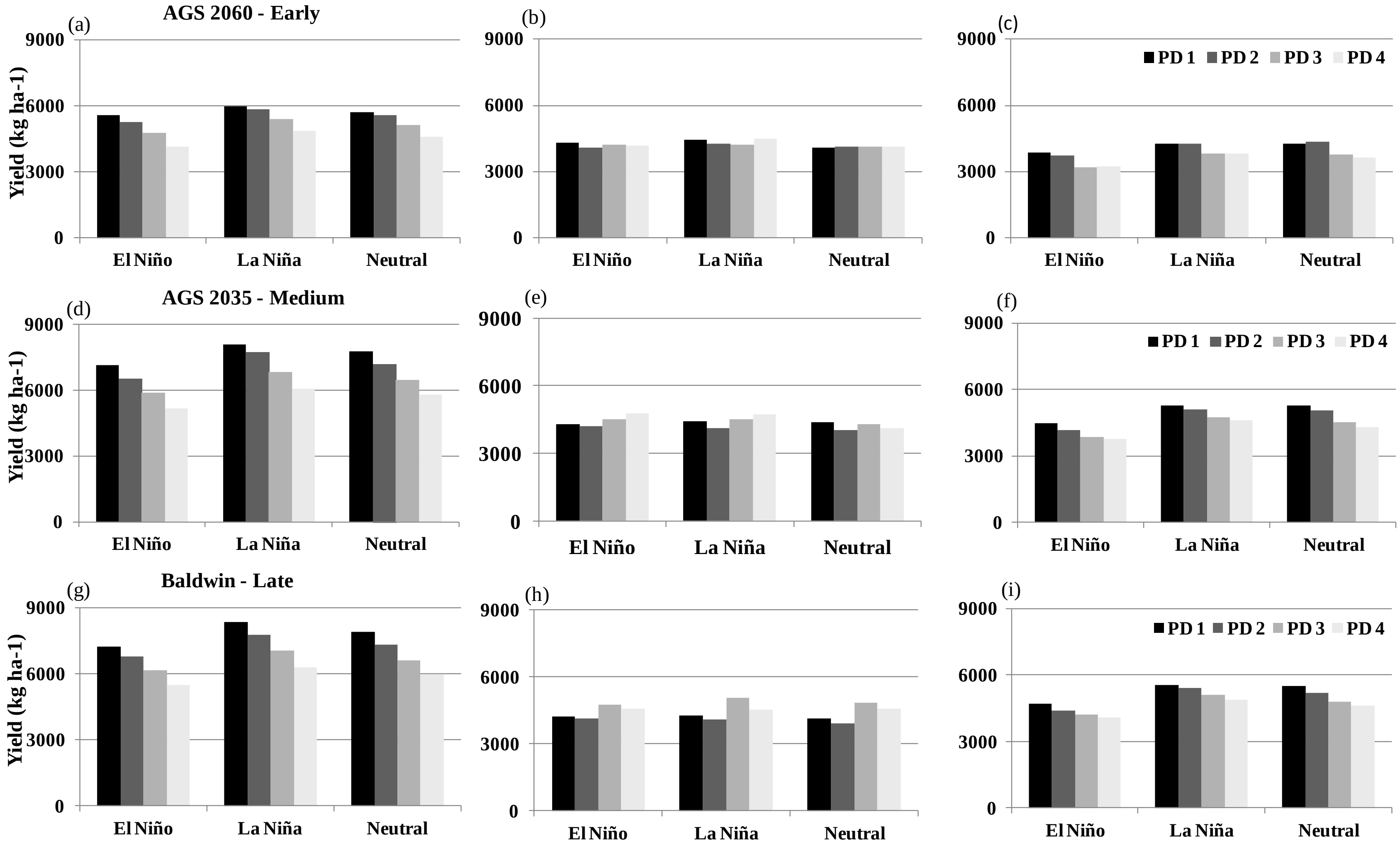

Fig. 13. Average simulated yield by ENSO phase of the three wheat varieties planted at four times during the growing season at Belle Mina (a,d,g), Shorter (b,e,h), and Headland (c,f,i), AL.