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Cotton yields as influenced by ENSO at different planting dates and spatial aggregation levels

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ABSTRACT

El Niño-Southern Oscillation (ENSO) is an important oceano-atmospheric phenomenon influencing crop production in the southeastern USA. Planting date is a major management variable that needs to be tailored to an anticipated ENSO event. Although ENSO effect may vary by planting date because crop season moves with planting date, no study has explored this effect for this region. Cotton (*Gossypium hirsutum* L.) production in Georgia is affected by ENSO, but no study has determined the ENSO effect at spatial scales smaller than a state. This study examined the ENSO effect on cotton yields in Georgia for various planting dates at three spatial levels: county, crop reporting district, and region. Using CROPGRO-Cotton, lint yields were simulated for 97 counties and 38–107 years, depending on county, each with nine planting dates within the planting window of April 10 through June 6. Yields were separated by ENSO phase, and tests were performed to find if yields were different across ENSO phases. Analyses at different levels showed different results regarding the ENSO effect. According to county level analyses, ENSO had little and spatially less consistent effect. The effect became more evident with a shift from smaller to larger level. According to regional level analysis, yield difference among ENSO phases was minimal for average planting dates, but substantial at the ends. For planting dates before May 9, yields during La Niña phases were higher than those during the other phases. For planting dates after May 23, however, yields during El Niño phases were higher.

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1. Introduction

In the state of Georgia, USA, agriculture is the largest industry (Georgia Farm Bureau, 2011), and among the field crops grown in the state, cotton ranks first in terms of acreage and economic value (National Agricultural Statistics Service (NASS), 2011). For the last several years, Georgia has ranked as the second state nationally with cotton planted in about 586,794 ha in 2011. With a production of 2.25 million bales in 2010, cotton brought in an estimated market value of $898 million to the state's economy (NASS, 2011).

Of all human activities, agriculture, especially rainfed, is the most weather-dependent (Oram, 1989). Of the various oceanic and atmospheric phenomena that influence the weather pattern of a particular location, the ones associated with the El Niño-Southern Oscillation (ENSO) are still the starting points for climate-related predictions (Fraisse et al., 2008). The ENSO refers to the year-to-year variation in sea surface temperatures, convective rainfall, surface air pressure, and atmospheric circulation that occur across the equatorial Pacific Ocean (Philander, 1990). The ENSO has been found to significantly affect crop production not only in many parts of the world (Garnett and Khandekar, 1992; Hammer et al., 2001; Podestá et al., 2002) but also in the southeastern USA (Garcia y Garcia et al., 2006; Handler, 1990; Hansen et al., 1998; Mavromatis et al., 2002; Phillips et al., 1999).

The impacts of ENSO on agriculture in this region are substantial, and so is the value of ENSO-based climate forecasts to agriculture (Jones et al., 2000; Solow et al., 1998). The strong teleconnection between ENSO and the weather conditions in this region has enabled skillful forecasting of seasonal temperature and precipitation up to one year in advance (Brolley et al., 2007; Steinemann, 2006). Predictions of climate variability associated with ENSO can potentially be used to reduce farm risk (Cabrera et al., 2006). ENSO predictions may help in tailoring crop management to make use or minimize the effects of the anticipated favorable or adverse weather conditions. Management practices tailored to ENSO phases – El Niño, La Niña, and neutral, which serve as a categorical measure of ENSO – might help growers make better management decisions and thus get higher yields (Garcia y Garcia et al., 2010; Paz et al., 2007).

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One of the important crop management practices that need to be tailored to the anticipated ENSO conditions is planting date, as it is one of the most important factors limiting crop yields. When irrigation is not an option, crop growers try to mitigate the effect of drought by selecting a planting date that minimizes water deficit. The adjustment of planting date according to environmental conditions could be useful for enhancing yields and reducing yield variability (Garcia y Garcia et al., 2010; Mavromatis et al., 2002; Nuti et al., 2006). In the southeastern USA, the impact of ENSO varies across seasons. For instance, fall, winter, and spring are generally wetter than usual during El Niño events (Kiladis and Diaz, 1989; Ropelewski and Halpert, 1986; Sittel, 1994a), whereas La Niña events tend to have wetter summers and drier winters and springs (Sittel, 1994a,b). Not all farmers plant the crop at one particular planting date, even in a particular area or location, due to variability in the production environment. They set their planting dates depending on their specific set of conditions. Thus, planting in a given location is done over a period of several days or weeks, called the planting window. Because the crop growing season changes with a change in planting date, the effect of ENSO is assumed to be different for different planting dates. For instance, the impact of ENSO on a crop planted on April 20 might be different from that on the crop planted on May 20. That is, the crop planted on April 20 might produce significantly different yields in El Niño and La Niña years, whereas the yields of the crop planted on May 20 may not be different in these years. Thus, to explore the impact of ENSO on crop yield in practical sense, the effect of ENSO needs to be investigated for each of several planting dates in the planting window. However, there have been no attempts so far to determine the effect of ENSO on cotton yield by planting date in Georgia or in the southeastern USA.

To consider the phenomena of microclimates and thus location-specific variability in weather conditions of a particular place in a particular time or period, it can be assumed that the effects of ENSO on cotton yields might be different when analyzed at different levels of spatial aggregation such as county, crop reporting district (CRD), and region. County may be considered as the smallest unit in the spatial scale. Although counties have been created for political purposes, their demarcations in the state of Georgia are generally based on physiographic features like lakes, rivers, mountains, hills, and watersheds. Therefore, each county may be considered a unique geographical division. The area of an average size county in Georgia is 967 km^2 (USG, 2012). A geographical unit that is larger than county in terms of spatial scale is a CRD. A CRD is a multi-county aggregate used for the purpose of recording agricultural information and reflects similar geography, soil types, and cropping patterns. A CRD in Georgia consists of, on an average, 18 counties. Above CRD lies the cotton belt of Georgia in terms of spatial scale. The cotton belt, which comprises 76 counties, is a major cotton production region in the state and covers most of the Coastal Plain which extends east and south of the Fall-Line Hills, the old Mesozoic shoreline marked by a line of sand hills (Hodler and Schretter, 1986). The Atlantic Ocean forms the eastern border, and the southern border of this province is formed by the Gulf of Mexico. The region is distinct physiographically and has soils of about the same origin and nature. No study has so far explored the effects of ENSO at smaller spatial scales than region or state such as the cotton belt, CRD, or county.

Using the CSM-CROPGRO-Cotton (Messina et al., 2004), a widely used cotton model (Garcia y Garcia et al., 2010, 2008; Pathak et al., 2007; Suleiman et al., 2007; Zamora et al., 2009) coupled to the Decision Support System for Agrotechnology Transfer (DSSAT: Hoogenboom et al., 2004; Jones et al., 2003), a suite of computer programs that facilitate the application of crop simulation models, this study examined the effect of ENSO on cotton yields in the state of Georgia as influenced by several planting dates at three different levels of spatial aggregation: county, CRD, and the cotton belt. It was hypothesized that the 'true' impact of ENSO in the region might vary depending on the level of spatial aggregation used in the analysis. For instance, a study conducted at a county level might conclude that the yield of a cotton crop planted in Mitchell County on May 1 in an El Niño year was not different from the one planted in a La Niña year. A regional level analysis, on the other hand, might come to the conclusion that the yields in these years were significantly different. The ENSO-related yield variability information at the largest spatial unit, the cotton belt, could be important for long-term commercial interests (Jagtap and Jones, 2002), strategic agricultural planning, and public policy formulation and application (de Wit et al., 2005; Lobell and Ortiz-Monasterio, 2006; Wassenaar et al., 1999). Policies or decisions based on the information at the largest level might benefit a majority of stakeholders in the cotton belt. The ENSO information at the smallest spatial unit (county) on the other hand, might be helpful to the crop producers of the immediate area with respect to management decisions, for instance, time of planting and irrigation. Predictions of a smaller spatial level study might be more accurate and helpful to the stakeholders than those of a larger spatial level study because the latter assumes that a physiographic feature is homogenous throughout a large region, which is generally not the case. The results of the larger spatial level analysis, however, might be helpful to the smaller spatial level stakeholders, especially from marketing point of view, as the results could show them the overall weather situations in other areas of the CRD and region, perhaps their competitors.

2. Materials and methods

2.1. Site description and weather data

For the study, 97 cotton producing counties in the state of Georgia, USA were chosen (Fig. 1). These counties lie within the region of (30.5°N, 81.2°W) and (34.7°N, 85.5°W). The landscape of the cotton production region runs from rolling hills in the north to the coastal plain in the south and southeast. The elevation of the region ranges from about 5 m to 300 m. This region, in general, has a humid subtropical climate with mild winters and hot moist summers (NETSTATE, 2012). The average annual precipitation across this region ranges from 1000 mm to 1500 mm (NOAA, 2008). Annual average afternoon high temperatures usually range from 29 °C to 33 °C, and average overnight low temperatures range from 18 °C to 24 °C (NOAA, 2009). The cotton model needs daily values of minimum and maximum air temperatures, precipitation, and solar radiation. Of the four weather variables, only the first three are generally recorded at most weather stations. The temperature and precipitation data were obtained from the website of the National Climatic Data Center (NCDC, 2011). Most of the counties selected for the study had their own weather stations and data. For those that did not have weather stations, the weather data were obtained from the nearest weather station in a neighboring county. The number of crop seasons considered for the simulation of cotton yield for a county depended on the availability of the weather data from the COOP station situated in the county. Thus, depending on counties, the weather data consisted of 38–107 years' daily records during the period of 1900 through 2006. Values of solar radiation, another important weather variable and key input for crop simulation, were generated using the Weather Generator for Solar Radiation (WGENR), a stochastic solar radiation generator developed by Hodges et al. (1985) and later modified for the southeastern USA by Garcia y Garcia and Hoogenboom (2005):

$$R_g = \rho\sigma + R_a + R_m\{\cos[0.0172(d - 172) + c]\}, \qquad (1)$$

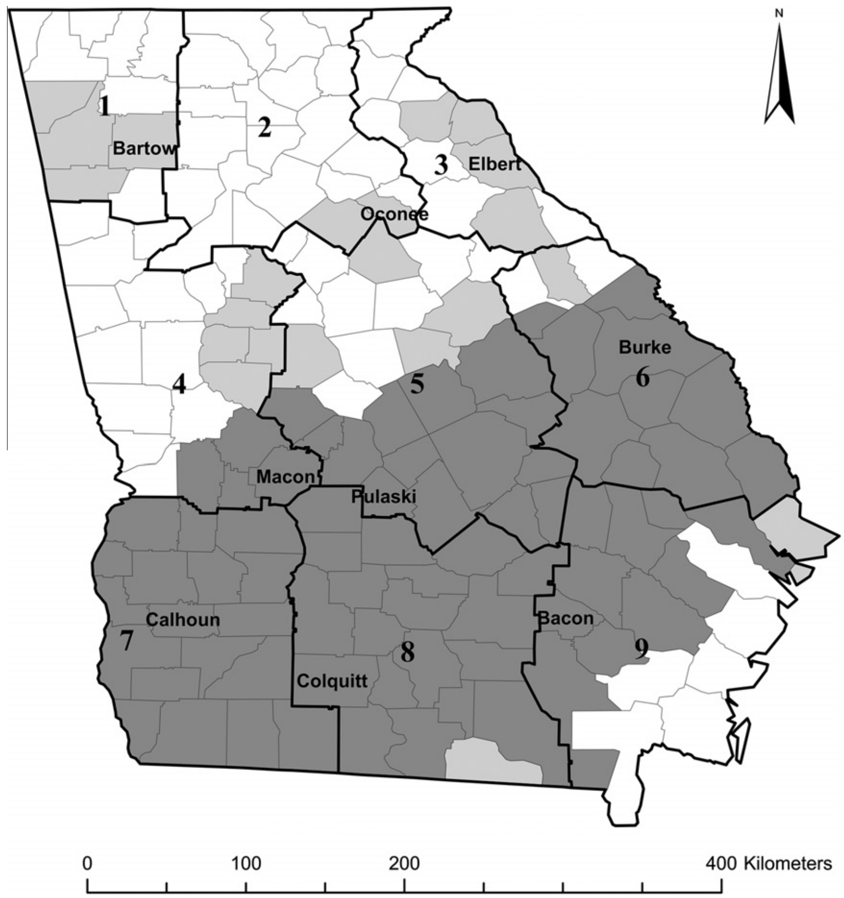

Fig. 1. Map showing the cotton producing counties in the state of Georgia, USA (all shaded), the Georgia cotton belt (the darker region), the nine crop reporting districts (numbered regions with bold borders), and the nine counties (name labeled) selected for the study.

where R_g is daily global solar radiation (MJ m^{-2} d^{-1}); ρ is a random component describing the correlation between temperature and R_g (Richardson, 1981); σ is the standard deviation conditioned to wet or dry days; R_a and R_m are annual average and amplitude solar radiation values, respectively; d is the day of year; and c is a constant which is 0 (183) for the northern (southern) hemisphere. For this study, WGENR was used because it has been used as a principal solar radiation generator for crop modeling purposes in the southeastern USA (Woli and Paz, 2012). For crop growth simulation purpose, three most dominant agricultural soil types were selected for each county based on the suitability to growing cotton and the proportion of availability in the county and used as the representative soils for that county. Soil type, however, was assumed to have no influence on ENSO effect. That is, the proportion of yield difference among ENSO phases was assumed to be the same for all soils. For each soil type, separate simulations were carried out. The profile and property information of these soils were obtained from the website of the USDA Natural Resources Conservation Service (NRCS, 2011a,b).

2.2. Yield simulations

For studies that involve crop yield responses to alternate environmental conditions, such as ENSO phases, and alternate management conditions, such as planting dates, crop models are the preferred choice (Mavromatis et al., 2002). Crop models can quantify the effects of several biophysical components and their interactions that an agricultural system is comprised of (Ahuja et al., 2007). Crop models can significantly shorten the experimental process involving various environmental conditions and management options (López-Cedrón et al., 2008). The response of cotton yield to different ENSO phases for various planting dates was explored using the CSM-CROPGRO-Cotton model. Daily weather data comprising the four weather variables mentioned above are its inputs, whereas the output variables are various plant growth components (including lint yield), plant carbon, plant/soil nitrogen balances, evapotranspiration, and soil water balance, among others. Daily soil water (W) balance is computed as: W = (initial soil water + irrigation + precipitation − water added with residue − mulch evaporation − deep drainage − tile drainage − surface runoff − soil evaporation − transpiration), all occurred in a day (mm d^{-1}). Several studies in the past have used this model for various purposes, such as improving irrigated cropping systems (Christopher, 2007), estimating irrigation water use (Guerra et al., 2007), sensitivity analysis of the model (Pathak et al., 2007), deficit irrigation management (Suleiman et al., 2007), adapting the model to include root-knot nematode parasitism (Ortiz et al., 2009), modeling cotton production response to shading (Zamora et al., 2009), and assessing the impact of generated solar radiation on cotton growth and yield and the effect of climatic variability on water use efficiency (Garcia y Garcia et al., 2008, 2010).

The CROPGRO-Cotton was evaluated for conditions in Georgia before simulating the yields. The model had already been calibrated for this region by previous researchers (Garcia y Garcia et al., 2008, 2010). For model evaluation, observed data for the variety DP 555 BG/RR from 2002 to 2007 obtained from variety trials conducted in Plains and Tifton in Georgia (http://www.swvt.uga.edu/) were used. Daily maximum and minimum air temperatures and precipitation for each location were obtained from the COOP network as compiled by the Center for Ocean-Atmospheric Prediction Studies

(COAPS) through the Southeast Climate Consortium (http://www.SEClimate.org). Daily values of solar radiation were generated from the observed daily air temperatures and rainfall using the WGENR. The soil profile information for each location was obtained from the soil characterization database of the USDA Natural Resources Conservation Service (NRCS, 2011a). Data from both rainfed and irrigated conditions were used for model evaluation. For the latter conditions, irrigation was automatically applied based on the threshold, called the management allowed depletion (MAD), the fraction of total plant available water capacity that is to be depleted from the active root zone before irrigation is applied. When soil water content in the management depth (50 cm) would fall below the threshold (MAD) of 60%, irrigation would be given to bring the water content back to the capacity. Other crop management practices, such as planting date and N-fertilizer application, were set according to normal practices recommended for Alabama and Georgia (Culpepper et al., 2009). The performance of the model was evaluated using the root mean square error (RMSE), the Willmott index (Willmott, 1981), and the modeling efficiency (ME) (Nash and Sutcliffe, 1970) as goodness-of-fit measures. The coefficient of determination (R^2) was also used to provide supplemental information. The RMSE denotes the average distance of a data point from the predicted values measured along a vertical line and is used to assess the error associated with prediction. The Willmott index is a measure of the degree to which the observed values are approached by the model-predicted values. The Willmott index measures the deviations from the perfect prediction line (1:1 line). The ME is the average distance between the observed and estimated values relative to the average distance between the observed and the mean observed values. An ME of 0 indicates that the model predictions are as accurate as the mean of the observed data, whereas an ME of 1 corresponds to a perfect match of the modeled values to the observed data. A greater ME value indicates that estimated values are closer to the observed values than the mean observed values. The R^2 describes the proportion of variability in the observed data that can be accounted for by the model. Its values range from 0 to l, with 1 meaning the perfect agreement between the observed and predicted values and 0 meaning no agreement at all.

After model evaluation, rainfed lint yields were simulated for each county and year using the seasonal cropping module (Thornton et al., 1994) of the DSSAT 4.5 software. Three dominant agricultural soils in each county were chosen as the representative soils for that county, and DP 555 was selected as the representative cotton variety for all counties. Simulations were carried out for each of the nine planting dates – April 10, April 17, April 24, May 2, May 9, May 16, May 23, May 30 and June 6 – chosen as the representative dates of the cotton planting window in Georgia which generally begins in April and continues until early June (Georgia Cotton Commission, 2011).

For each planting date, once the lint yields were simulated for each of the 97 counties (for all years), the counties were then separated or aggregated into different groups for spatial analyses. The effect of ENSO was analyzed at three levels of spatial aggregation: county, CRD, and region. The state of Georgia is divided into nine CRDs (Fig. 1). At CRD level, yields for all counties within a CRD were separately simulated and then averaged. For the county level study, a county with the highest average yield was selected as the representative county from each CRD based on the data from 1950 to 2007 (NASS, 2011). The intent of selecting the representative county on the basis of the highest yield was to examine the effect of ENSO on cotton yields produced in a land that is most productive or suitable for growing cotton. These counties were Bacon, Bartow, Burke, Calhoun, Colquitt, Elbert, Macon, Oconee, and Pulaski (Fig. 1). For each of these counties, cotton yield was separately simulated using the weather data available for that county. For the regional level analysis, the major cotton production region in Georgia was delineated by creating a regional boundary map based on the 2007 county yield data reported by the USDA National Agricultural Statistics Service. This region covers most of the Coastal Plain and encompasses several counties in CRDs 4 and 5 and most of the counties in CRDs 6 through 9 (Fig. 1). The regional level yields were computed by averaging the yields for all counties within the region which were separately simulated.

Once yields were simulated for each county (with all years) and separated for county level of study and aggregated for CRD and regional level of analyses, they were split into three ENSO phases which were characterized using the Japanese Meteorological Association Index (JMAI) as an indicator (COAPS-FSU, 2010). The JMAI is a 5-month running mean of spatially-averaged sea surface temperature anomalies over the tropical pacific region (4°S–4°N, 150°W–90°W). In its standard application, an El Niño (or La Niña) episode is defined when the JMAI is greater than or equal to 0.5 °C (or less than or equal to −0.5 °C) for six consecutive months, including October through December. The episode then lasts from October through the following September. The episode for all other values of JMAI is termed Neutral.

2.3. Statistical analyses

Tests were performed to find out if lint yields were significantly different across the three ENSO phases. Such analyses were carried out for the region, for each of the nine CRDs, for each of the nine counties, and for each planting date. Because the assumption of normality was not met for each aggregation level, planting date, and ENSO-phase, the Kruskal–Wallis procedure, a nonparametric alternative to the classical one-way analysis of variance (ANOVA) test and an extension of the Wilcoxon rank sum test to more than two groups, was used (MathWorks, 2012a). The Kruskal–Wallis test compares samples from two or more groups using their medians with the null hypothesis that all samples are drawn from the same population or from different populations with the same distribution. The ANOVA table of this test is calculated using the ranks of the data rather than their numeric values. The ranks are obtained by ordering the data from the smallest to the largest observation across all groups and taking the numeric index of this ordering. The *F* statistic of the classical one-way ANOVA is replaced by a chi-square statistic. The *p* values measures the significance of the chi-square statistic. The *p* value close to zero suggests that at least one sample median is significantly different from the others. For further information about which pairs of mean ranks were significantly different and which were not, the multiple (pair-wise) comparison procedure was used (MathWorks, 2012b) with the Tukey–Kramer LSD test.

3. Results and discussion

3.1. Model evaluation

Values of the goodness-of-fit measures used to evaluate the CSM-CROPGRO-Cotton showed that the model simulated lint yields of cotton in agreement with the observed data (Fig. 2). The Willmott index of 0.9 as well as the modeling efficiency of 0.7 indicated that the ability of the model to simulate cotton yields for Georgia in general was very good. Although the model performance was slightly better for Plains than for Tifton, the performance was generally good for both locations in Georgia (Table 1). The efficiency of the model was better for rainfed condition than for irrigated one. According to the Nash–Sutcliffe index, the model performance was good for rainfed condition, but poor for irrigated condition. According to the Willmott index, however, the performance was good also for irrigated condition. According

Table 1
Values of the goodness-of-fit measures used to evaluate the performance of the CROPGRO-Cotton model used for simulating cotton yields for the state of Georgia, USA.

Measure	Unit	Overall	Location		Condition	
			Plains	Tifton	Irrigated	Rainfed
Root mean square error (RMSE)	kg ha^{-1}	252	220	272	274	227
Willmott index	–	0.90	0.93	0.85	0.74	0.88
Nash–Sutcliffe index	–	0.70	0.74	0.57	0.04	0.43
Coefficient of determination (R^2)	–	0.70	0.75	0.59	0.50	0.72

to the R^2 values, about 50–72% of the variability in the observed data could be accounted for by the model, depending on the condition and location.

3.2. County level analysis

According to county level analyses, the impacts of ENSO on cotton yields were different for different counties (Table 2). Except for Burke and Calhoun, the yield differences across ENSO phases for the other counties were insignificant. Even for Burke and Calhoun counties, the differences were only for a few planting dates or not across all the phases. These results indicated that the effect of ENSO varies by counties, which might be due to the variability in local climate. The effect of ENSO was probably masked by location-specific weather conditions which are generally defined by physiographic features such as lakes, rivers, hills, mountains, and forests, which vary from location to location. Counties whose physiographic features were not evident or not strong enough to create a microclimate probably had significant effect of ENSO. On the other hand, counties whose geographic features were effective enough to create location-specific microclimates were probably not affected by ENSO due to the moderation of ENSO effect by local climate effect. Although the yield differences across ENSO phases were not significant, yields in La Niña years were generally higher than those in El Niño and neutral years for crops planted by the middle of May in most of the nine counties evaluated here. For crops planted after May 16, however, El Niño years had higher yields than La Niña and neutral years. In Georgia, cotton crops planted on April 10, May 16, and June 6 mature approximately at the end of August, September, and October, respectively (Georgia Cotton Commission, 2011; Ritchie et al., 2004), indicating that the main growing season of a cotton crop generally falls in summer months. During summer, La Niña years tend to be slightly wetter and thus cooler than normal years in the southeastern USA in general (Sittel, 1994a, 1994b). Due to relatively more precipitation and lower temperature during the main growing season, crops that matured before the end of September yielded more in La Niña years than in other years. But the crops that were planted late in the season (after May 16) extended their growing seasons until the end of October. Because from October through April El Niño years tend to be wetter than normal years, yields in El Niño years were higher than in other years for crops planted after May 16. These results indicated that the actual effect of ENSO on cotton yields for a particular location depends on planting date. Unlike

Table 2
Median lint yields (kg ha^{-1}) associated with various planting dates, ENSO phases, and counties in Georgia, USA.

County	ENSO	Planting date								
		April 10	April 17	April 24	May 2	May 9	May 16	May 23	May 30	June 6
Bartow	Neutral	1516[a,A]	1522[a]	1546[a]	1538[a]	1543[a]	1524[a]	1485[a]	1438[a]	1258[a]
	El Niño	1526[a]	1466[a]	1575[a]	1532[a]	1621[a]	1514[a]	1453[a]	1376[a]	1284[a]
	La Niña	1720[a]	1705[a]	1704[a]	1723[a]	1715[a]	1657[a]	1614[a]	1489[a]	1218[a]
Oconee	Neutral	724[a]	723[a]	723[a]	730[a]	780[a]	777[a]	740[a]	695[a]	707[a]
	El Niño	749[a]	725[a]	797[a]	842[a]	845[a]	836[a]	793[a]	796[a]	762[a]
	La Niña	776[a]	776[a]	752[a]	791[a]	851[a]	840[a]	780[a]	737[a]	698[a]
Elbert	Neutral	1105[a]	1099[a]	1107[a]	1114[a]	1062[a]	1049[a]	991[a]	890[a]	760[a]
	El Niño	1232[a]	1237[a]	1230[a]	1194[a]	1179[a]	1098[a]	1055[a]	948[a]	820[a]
	La Niña	1251[a]	1291[a]	1258[a]	1199[a]	1177[a]	1120[a]	1044[a]	948[a]	796[a]
Macon	Neutral	1259[a]	1276[a]	1304[a]	1314[a]	1315[a]	1313[a]	1276[a]	1250[a]	1236[a]
	El Niño	1225[a]	1252[a]	1239[a]	1276[a]	1244[a]	1288[a]	1264[a]	1250[a]	1246[a]
	La Niña	1268[a]	1288[a]	1313[a]	1320[a]	1314[a]	1311[a]	1249[a]	1242[a]	1238[a]
Pulaski	Neutral	1475[a]	1485[a]	1516[a]	1534[a]	1537[a]	1534[a]	1507[a]	1456[a]	1397[a]
	El Niño	1496[a]	1515[a]	1519[a]	1558[a]	1575[a]	1552[a]	1534[a]	1479[a]	1425[a]
	La Niña	1476[a]	1464[a]	1497[a]	1524[a]	1533[a]	1541[a]	1501[a]	1422[a]	1358[a]
Burke	Neutral	1054[b]	1026[b]	1043[b]	1058[b]	1073[a]	1085[a]	1048[a]	993[b]	950[b]
	El Niño	1058[b]	1021[b]	1038[b]	1048[ab]	1069[a]	1135[a]	1098[a]	1120[a]	1039[a]
	La Niña	1198[a]	1262[a]	1200[a]	1197[a]	1213[a]	1168[a]	1080[a]	1085[ab]	982[ab]
Calhoun	Neutral	1426[b]	1402[ab]	1422[b]	1415[b]	1392[b]	1363[b]	1321[b]	1279[b]	1256[b]
	El Niño	1490[a]	1490[a]	1503[a]	1507[a]	1492[a]	1492[a]	1441[a]	1416[a]	1346[a]
	La Niña	1339[b]	1345[b]	1340[b]	1386[b]	1368[b]	1339[b]	1302[b]	1278[b]	1244[b]
Colquitt	Neutral	1051[a]	1057[a]	1079[a]	1101[a]	1098[a]	1082[a]	1061[a]	1041[a]	996[a]
	El Niño	1038[a]	1080[a]	1057[a]	1100[a]	1091[a]	1070[a]	1100[a]	1026[a]	982[a]
	La Niña	1088[a]	1124[a]	1125[a]	1120[a]	1110[a]	1093[a]	1063[a]	980[a]	966[a]
Bacon	Neutral	1409[ab]	1430[a]	1463[a]	1462[a]	1470[a]	1443[a]	1428[a]	1390[a]	1324[a]
	El Niño	1334[b]	1405[a]	1407[a]	1436[a]	1457[a]	1419[a]	1414[a]	1392[a]	1335[a]
	La Niña	1461[a]	1452[a]	1494[a]	1496[a]	1457[a]	1432[a]	1399[a]	1353[a]	1304[a]

[A] Yields followed by the same letter across ENSO phases within a county and planting date are not significantly different at $P < 0.05$ by the Tukey–Kramer LSD test.

other counties, Calhoun had significantly higher yields in El Niño years than in the other ENSO phases for all planting dates. Calhoun lies in a region where Alabama, Florida, and Georgia meet, called the Tri-State region. In this region, El Niño (La Niña) years are wetter (drier) than normal years during April, May, and June (Fraisse et al., 2006). Possibly because of more precipitation, therefore, yields in Calhoun in El Niño years were higher than those in the other years.

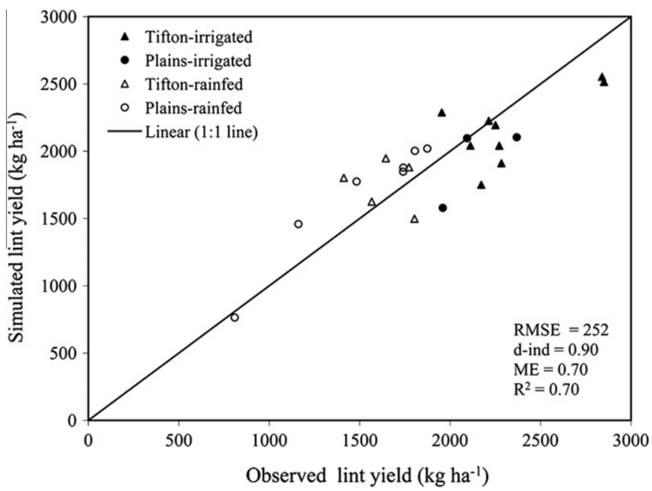

Fig. 2. The simulated versus observed lint yields of cotton for two locations in the state of Georgia, USA, from year 2002 to 2007. Note: RMSE = root mean square error, d-ind = the Willmott index, ME = the modeling efficiency (Nash–Sutcliffe index), and R^2 = coefficient of determination.

3.3. District level analysis

At the CRD level of aggregation, no significant yield difference was found across ENSO phases for all planting dates for CRDs 1, 2, and 3 which lie in the northern part of the state (Table 3). The insignificant difference across ENSO phases for all counties in the northern part of Georgia at both county and CRD level of aggregation indicated that the ENSO signal especially during cotton growing season is weak in this part of the state. This inference conforms to the statement of Fraisse et al. (2006) that the northern parts of Alabama and Georgia do not have ENSO effects during summer. The ENSO signals have been found to be weak in the northern and central parts of Alabama and Georgia (AgroClimate, 2011). For CRDs in the central and southern parts, yield differences across ENSO phases were significant for several planting dates, suggesting that the ENSO signal is strong enough to have impact on the climate of these areas. For most CRDs in the central and southern parts, the significant yield differences were generally associated with the planting dates in the first half of the planting window, and La Niña (El Niño) years had significantly higher (lower) yields than neutral years. The higher yields in La Niña years associated with crops planted before the middle of May were due to wetter conditions in this phase until the end of September. The higher yields in El Niño years for the crops planted later in the season, such as May 30 and June 6, were also due to wetter conditions because the seasons of these crops extend to the end of October, when an El Niño (La Niña) year has already started receiving more (less) precipitation than a normal year. These phenomena led to increase in El Niño yields and decrease in La Niña yields and thus to insignificant yield difference. The CRD 7 was different from the other CRDs in that El Niño (La Niña) years had significantly higher (lower) yields than neutral years, and that the significant difference was associated with the planting dates in the terminal half

Table 3
Median lint yields (kg ha^{-1}) related to various planting dates, ENSO phases, and climate districts in Georgia, USA.

District	ENSO	Planting date								
		April 10	April 17	April 24	May 2	May 9	May 16	May 23	May 30	June 6
1	Neutral	1505^{a}[A]	1514^{a}	1528^{a}	1520^{a}	1512^{a}	1484^{a}	1445^{a}	1365^{a}	1237^{a}
	El Niño	1491^{a}	1506^{a}	1507^{a}	1502^{a}	1482^{a}	1455^{a}	1409^{a}	1316^{a}	1176^{b}
	La Niña	1582^{a}	1571^{a}	1587^{a}	1572^{a}	1551^{a}	1507^{a}	1453^{a}	1370^{a}	1218^{a}
2	Neutral	1656^{a}	1656^{a}	1663^{a}	1673^{a}	1688^{a}	1672^{a}	1648^{a}	1605^{a}	1479^{a}
	El Niño	1664^{a}	1678^{a}	1700^{a}	1693^{a}	1704^{a}	1702^{a}	1684^{a}	1629^{a}	1512^{a}
	La Niña	1727^{a}	1741a	1731^{a}	1723^{a}	1740^{a}	1702^{a}	1679^{a}	1621^{a}	1502^{a}
3	Neutral	1232^{a}	1233^{a}	1251^{a}	1248^{a}	1252^{a}	1229^{a}	1186^{a}	1156^{a}	1064^{a}
	El Niño	1202^{a}	1212^{a}	1236^{a}	1237^{a}	1240^{a}	1216^{a}	1187^{a}	1157^{a}	1069^{a}
	La Niña	1291^{a}	1291^{a}	1270^{a}	1266^{a}	1264^{a}	1240^{a}	1198^{a}	1141^{a}	1030^{a}
4	Neutral	1342^{ab}	1355^{ab}	1375^{a}	1367^{a}	1374^{a}	1348^{a}	1312^{a}	1270^{b}	1212^{b}
	El Niño	1324^{b}	1344^{b}	1359^{a}	1364^{a}	1372^{a}	1356^{a}	1332^{a}	1298^{ab}	1236^{ab}
	La Niña	1365^{a}	1380^{a}	1388^{a}	1390^{a}	1388^{a}	1379^{a}	1348^{a}	1315^{a}	1254^{a}
5	Neutral	1330^{b}	1343^{b}	1359^{b}	1378^{ab}	1365^{ab}	1353^{a}	1330^{a}	1296^{a}	1236^{a}
	El Niño	1298^{b}	1313^{b}	1344^{b}	1363^{b}	1352^{b}	1346^{a}	1336^{a}	1313^{a}	1256^{a}
	La Niña	1370^{a}	1375^{a}	1396^{a}	1397^{a}	1392^{a}	1369^{a}	1342^{a}	1290^{a}	1231^{a}
6	Neutral	1182^{b}	1198^{b}	1232^{b}	1236^{b}	1248^{b}	1229^{b}	1206^{b}	1180^{a}	1110^{a}
	El Niño	1170^{b}	1175^{b}	1216^{b}	1228^{b}	1230^{b}	1219^{b}	1208^{ab}	1185^{a}	1124^{a}
	La Niña	1292^{a}	1298^{a}	1311^{a}	1315^{a}	1305^{a}	1278^{a}	1243^{a}	1202^{a}	1139^{a}
7	Neutral	1376^{a}	1395^{a}	1418^{a}	1431^{a}	1424^{ab}	1419^{b}	1400^{b}	1364^{b}	1317^{b}
	El Niño	1381^{a}	1399^{a}	1428^{a}	1445^{a}	1444^{a}	1445^{a}	1437^{a}	1407^{a}	1355^{a}
	La Niña	1375^{a}	1391^{a}	1413^{a}	1424^{a}	1417^{b}	1406^{b}	1386^{b}	1346^{b}	1305^{b}
8	Neutral	1403^{b}	1420^{b}	1446^{b}	1458^{ab}	1461^{ab}	1455^{a}	1431^{a}	1399^{a}	1357^{a}
	El Niño	1362^{c}	1400^{b}	1428^{b}	1442^{b}	1440^{b}	1437^{a}	1415^{a}	1393^{a}	1354^{a}
	La Niña	1446^{a}	1452^{a}	1477^{a}	1481^{a}	1477^{a}	1462^{a}	1422^{a}	1381^{a}	1339^{a}
9	Neutral	1422^{b}	1438^{b}	1472^{b}	1480^{b}	1484^{a}	1465^{a}	1450^{a}	1416^{a}	1348^{a}
	El Niño	1404^{b}	1426^{b}	1468^{b}	1473^{b}	1467^{a}	1457^{a}	1435^{a}	1416^{a}	1361^{a}
	La Niña	1482^{a}	1500^{a}	1513^{a}	1514^{a}	1504^{a}	1484^{a}	1456^{a}	1408^{a}	1346^{a}

[A] Yields followed by the same letter across ENSO phases within a district and planting date are not significantly different at $P < 0.05$ by the Tukey–Kramer LSD test.

Table 4
Median lint yields (kg ha^{-1}) associated with various planting dates and ENSO phases for the cotton belt in Georgia, USA.

ENSO	Planting date								
	April 10	April 17	April 24	May 2	May 9	May 16	May 23	May 30	June 6
Neutral	1329^{bA}	1346^{b}	1377^{b}	1384^{b}	1385^{a}	1376^{a}	1354^{a}	1321^{b}	1268^{b}
El Niño	1318^{b}	1337^{b}	1372^{b}	1384^{b}	1386^{a}	1381^{a}	1364^{a}	1337^{a}	1293^{a}
La Niña	1366^{a}	1380^{a}	1405^{a}	1407^{a}	1400^{a}	1386^{a}	1354^{a}	1311^{b}	1260^{b}

[A] Yields followed by the same letter across ENSO phases within a planting date are not significantly different at $P < 0.05$ by the Tukey–Kramer LSD test.

of the planting window. This district lies in the Tri-State region where an El Niño (La Niña) year is wetter (drier) than a normal year not only during the summer but also during the fall (Fraisse et al., 2006). Because of these phenomena, the yield difference between El Niño and La Niña became more evident for crops planted later in the season. For the initial planting dates, however, the difference across ENSO phases was insignificant probably due to insignificant difference in temperature. The portrayal of yield difference across ENSO phases in the central and southern parts of the state as significant according to CRD level analyses and as insignificant according to county level analyses implied that most of the counties that were not selected for the county level analysis had significantly different yields across ENSO phases, which further confirmed that ENSO is spatially less consistent when analyzed at a county level.

3.4. Regional level analysis

At a regional level, cotton yields in La Niña years were significantly greater than those in the other phases for crops planted until May 2 (Table 4). For crops planted from May 9 through May 23, no significant yield difference was found between El Niño and La Niña phases. For crops planted after May 23, yields in El Niño years were significantly greater than those in neutral and La Niña years. The growing season of the crop planted on April 10 reached up to the end of August, and the period of the most critical stages of water requirement of this crop, peak flowering and boll formation, fell around the middle of June to the first week of July. Because a La Niña year receives more precipitation than the other years during the summer, yield differences among the ENSO phases at this planting date were the greatest of all planting dates. But with a weekly shift in the planting date towards the first week of June, the crop growing season also moved towards fall, with October end being the edge of the last crop season. Because La Niña years are wetter during the summer, whereas El Niño years are wetter during the fall, with every delay in planting, crops got less and less water in La Niña years and more and more water in El Niño years. Thus, the yield difference between El Niño and La Niña years was significant only for crops planted early and late in the season. Yields of the crops planted in the middle of the planting window, such as May 9, May 16, and May 23, were not significantly different across ENSO phases because, the crop seasons being in the transitional phase of La Niña and El Niño, these crops received about the same amount of precipitation.

According to county and district level analyses, the effect of ENSO was inconsistent across counties and CRDs. Some counties and CRDs did not have the effect, and the others that had the effect were also inconsistent in terms of the effect for a particular planting date and whether the El Niño or La Niña years had the higher yields. The regional level analysis aggregated all these variations and provided a general picture of ENSO effect for the cotton belt.

4. Conclusion

Analyses at different levels of aggregation showed different results regarding the effect of ENSO on cotton yields in Georgia. According to county level analyses, ENSO had little and spatially less consistent effect on cotton yields in the counties selected. The effects became more evident with a shift from smaller to larger aggregation levels. According to the regional level analysis, the effect of ENSO in the cotton belt was very clear for each planting date selected in the planting window.

The effect of ENSO on cotton yields was not the same for all planting dates. The yield differences among ENSO phases were minimal for intermediate planting dates. The differences, however, were substantial for the planting dates in the initial and terminal parts of the planting window. For planting dates of April 10 through May 2, yields in a La Niña year were significantly higher than those in the other years. For planting dates of May 30 and June 6, yields in an El Niño year were significantly higher than those in the other years. The significantly higher yields with initial planting dates in La Niña years and with terminal planting dates in El Niño years were due to the amount of precipitation the crops received during their growing seasons. These trends should be considered by farmers as they determine their management strategies.

Results indicated that aggregating yield estimates at a county or CRD level may not be adequate to provide a definite interpretation of ENSO impacts. Neighboring counties or CRDs may have dissimilar and varying degrees of ENSO effects which cannot be used to translate into tangible options for decision makers. Yield aggregation at a regional level may provide a general picture of ENSO effect for the cotton belt. While the regional level information may be helpful at a policy or management level, it can be misleading at a county level, especially for the counties whose local climate is unique enough to moderate the ENSO effect. The results may have important implications on research areas related to downscaling observed or simulated values and uncertainties tied to weather parameters.

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