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A sod-based cropping system for irrigation reductions

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Abstract

Cotton and peanut grown under irrigation make up over 769,000 ha in the Southeast USA. The consumptive use of water for irrigation has significantly impacted groundwater resources, spring flows and streamflows in many parts of this region, particularly during severe droughts. This situation is further complicated with extreme weather events and climate variability. In this study, we compare yields and water use in a non-irrigated sod-based rotation system (SBR; bahiagrass–bahiagrass–peanut–cotton) to an irrigated conventional rotation system (ICR; peanut–cotton–cotton). Root mass of oat cover crop following peanut or cotton in a SBR and ICR system was also measured. A soil water assessment model (SWAT) was used to simulate irrigation water demands over a 34 yr period (1980–2013) under different soil types to quantify water saving potential of SBR. The average peanut yield in ICR from 2002 to 2013 was 4509 kg ha^{-1}, while that in SBR was 4874 kg ha^{-1}. Likewise the average cotton yield in ICR during the same period was 1237 kg ha^{-1}, while that in SBR was 1339 kg ha^{-1}. Oats had greater root mass in SBR than ICR. Simulation results indicate that crops in SBR consistently had substantially lower irrigation requirements (between 11 and 22 cm yr^{-1}) than those in ICR in dry years. The water-saving potential of SBR varies positively with increasing sand content in soil.

Key words: crop rotation, crop water demand, irrigation, perennial grasses, rooting depth

Introduction

Agricultural water withdrawals constitute 70% of all fresh-water withdrawals globally and up to 95% in developing countries[1]. Climate variability renders global water resources more vulnerable in light of an increasing demand and competing uses[1–4]. As a response to increasing demands on water resources, research needs to be directed toward increasing irrigation efficiency, improving crop water-use efficiency and making water conserving production practices adoptable.

Rotations of row crops with perennial grasses are more environmentally and economically sustainable than short-term rotations (such as peanut–cotton or soybean–corn, etc.) due to enhanced soil health, increased yields and reduced inputs[5,6]. Perennial grasses have proven to be useful in rotations due to their ability to develop deep root systems that can penetrate through compacted soil layers, increasing water infiltration and improving soil structure[7–10]. In addition to improving soil physical properties, perennial grasses improve soil organic C and N status and control pests when used in rotation with annual row crops[9–13].

At the North Florida Research and Education Center in Quincy, FL, we compared a non-irrigated 4-yr bahiagrass (*Paspalum notatum* F)–bahiagrass–peanut (*Arachis hypogea* L)–cotton (*Gossypium hirsutum* L) rotation (sod-based rotation; SBR) with an irrigated conventional 3-yr peanut–cotton–cotton rotation (ICR). We define SBR as a rotation comprising at least 2 yr of a perennial grass followed by annual row crops. Both SBR and ICR included a winter cover crop after the annual crops and employed conservation tillage. Some advantages of the SBR observed over the course of our 15 yr study were improved water and nitrogen use efficiency, lower soil bulk density, greater activity of nutrient cycling enzymes, greater fungal to bacterial ratio and greater number of beneficial fungal populations[6,14–17]. Peanut and cotton yield increases have consistently been observed following 2 yr of bahiagrass[6,11,14,18]. Crop yield increases

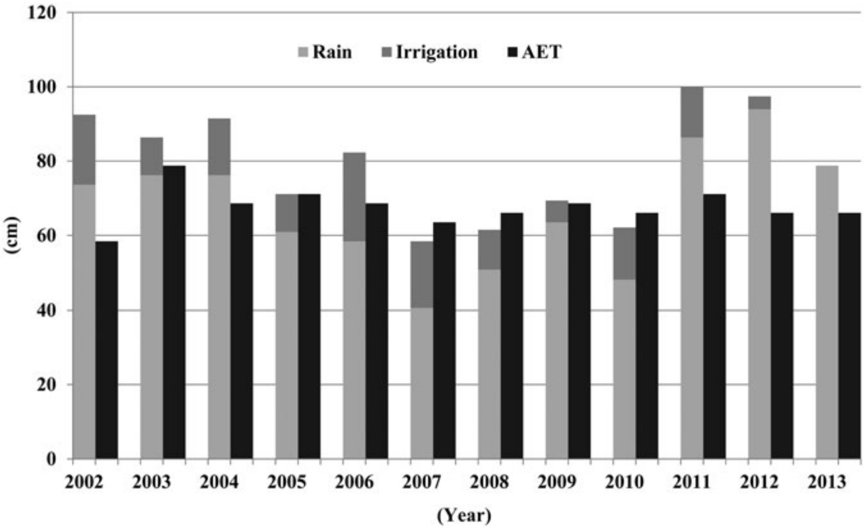

Figure 1. Comparison of annual irrigation plus rainfall with AET for cotton at the North Florida Research and Education Center, Quincy, FL.

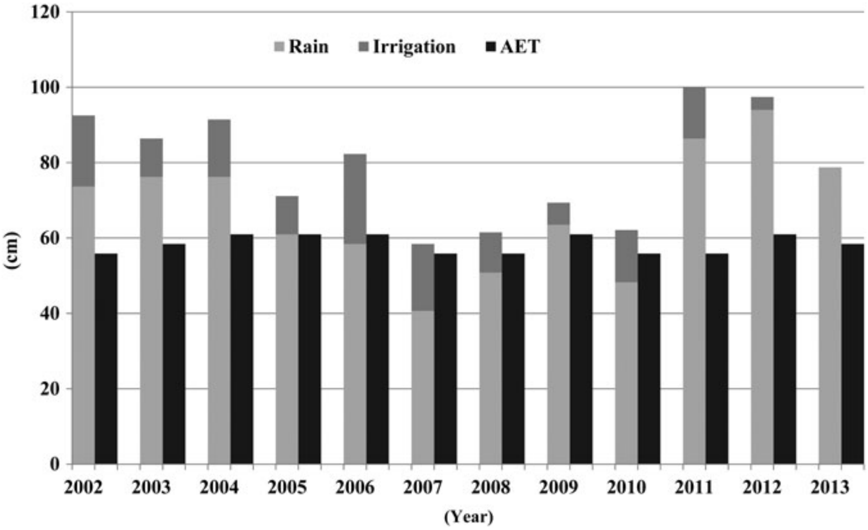

Figure 2. Comparison of annual irrigation plus rainfall with AET for peanut at the North Florida Research and Education Center, Quincy, FL.

from SBR can be attributed to greater soil organic matter due to bahiagrass, lower disease incidence and enhanced soil physical properties. Increased organic matter and lower bulk density result in better water retention and provide greater root access to plant available water[14]. Greater root biomass in the annual crops under SBR than ICR suggests a greater potential for efficient water and nutrient extraction in the former[8,14,16].

In the Southeast USA, farmers mainly employ high-input short-term rotations of annual crops (peanut–cotton) resulting in degradation of soil and water through increased soil erosion, loss of organic matter, increased contamination of surface and groundwater, increased incidence of pests and nematodes and increased emission of greenhouse gases[10,19,20]. Farming in the Southeast has also placed large irrigation demands on the Apalachicola–Chattahoochee–Flint River Basin resulting in surface and ground water decline since the 1970s[21]. For these reasons this region is particularly well-suited for rotations that improve soil quality and crop water-use efficiency. According to the USDA[22] much of agricultural irrigation in the Southeast USA is used for approximately 769,000 ha of cotton and peanut. Other crops in this region that have large irrigated areas are corn and soybeans with corn receiving the highest percentage of irrigation water. These irrigated areas present an opportunity where SBR can be implemented to reduce demand for irrigation. The objectives of this study were to: (1) quantify the range of irrigation reductions in the SBR system over ICR by simulating

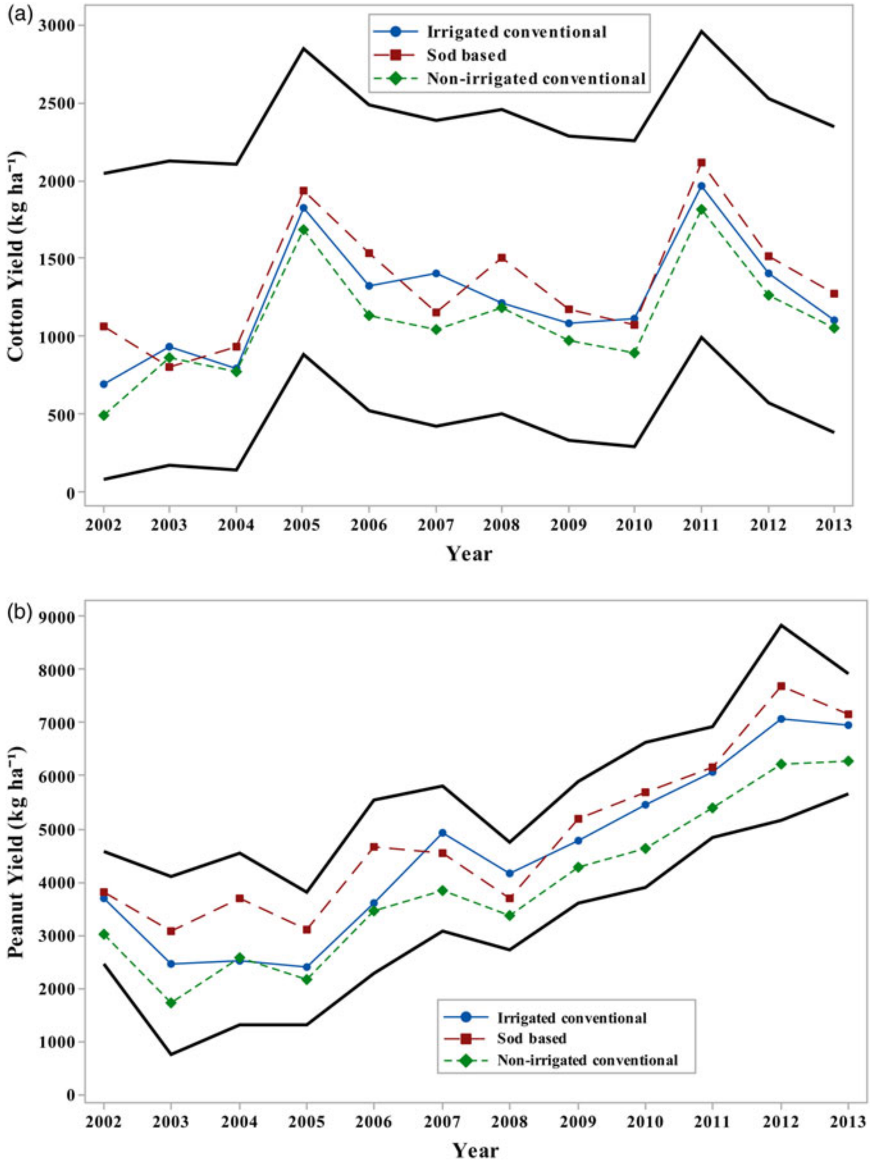

Figure 3. (a) Cotton yield from 2002 to 2013 in a non-irrigated SBR (bahiagrass–bahiagrass–peanut–**cotton**), ICR (peanut–**cotton**–cotton) and non-irrigated conventional rotation (peanut–**cotton**–cotton) at the North Florida Research and Education Center, Quincy, FL. Upper and lower 95% confidence limits are shown. (b) Peanut yield data from 2002 to 2013 in a non-irrigated SBR (bahiagrass–bahiagrass–**peanut**–cotton) and irrigated conventional rotation (ICR; **peanut**–cotton–cotton) and non-irrigated conventional rotation (**peanut**–cotton–cotton) at the North Florida Research and Education Center, Quincy, FL. Upper and lower 95% confidence limits are shown.

irrigation demands on three soil types based on weather data from 1980 to 2013; and (2) determine the differences in peanut and cotton yield and cover crop performance between SBR and ICR.

Materials and Methods

Experimental site and management history

The research was initiated in 2000 at the North Florida Research and Education Center, Quincy, Florida (30° 32.79′N, 84°35.50′W) on a Dothan sandy loam soil (fine, loamy siliceous, thermic Plinthic Kandiudults). Below 33 cm the soil is a clay loam. Treatments were arranged in a split-block experimental design with three replications. Each block was $128 \times 45.7\ m^2$, consisting of alternating irrigated and non-irrigated treatments. Each subplot was $45.7 \times 18.3\ m^2$ (20 rows) and these were aligned perpendicular to the irrigated and non-irrigated strips. A strip tillage unit (Kelly Manufacturing Co., KMC) was used to rip rows (in-row subsoiling) through cover crops to plant cotton and peanuts. Irrigated plots received 3 cm of water weekly (irrigation and precipitation) as recommended in the Georgia Crop Production Guide. Every crop phase (1st year bahiagrass, 2nd year bahiagrass, peanut, cotton in the SBR or peanut, 1st year cotton, 2nd year cotton in the ICR) was represented every year. All crops were planted between early

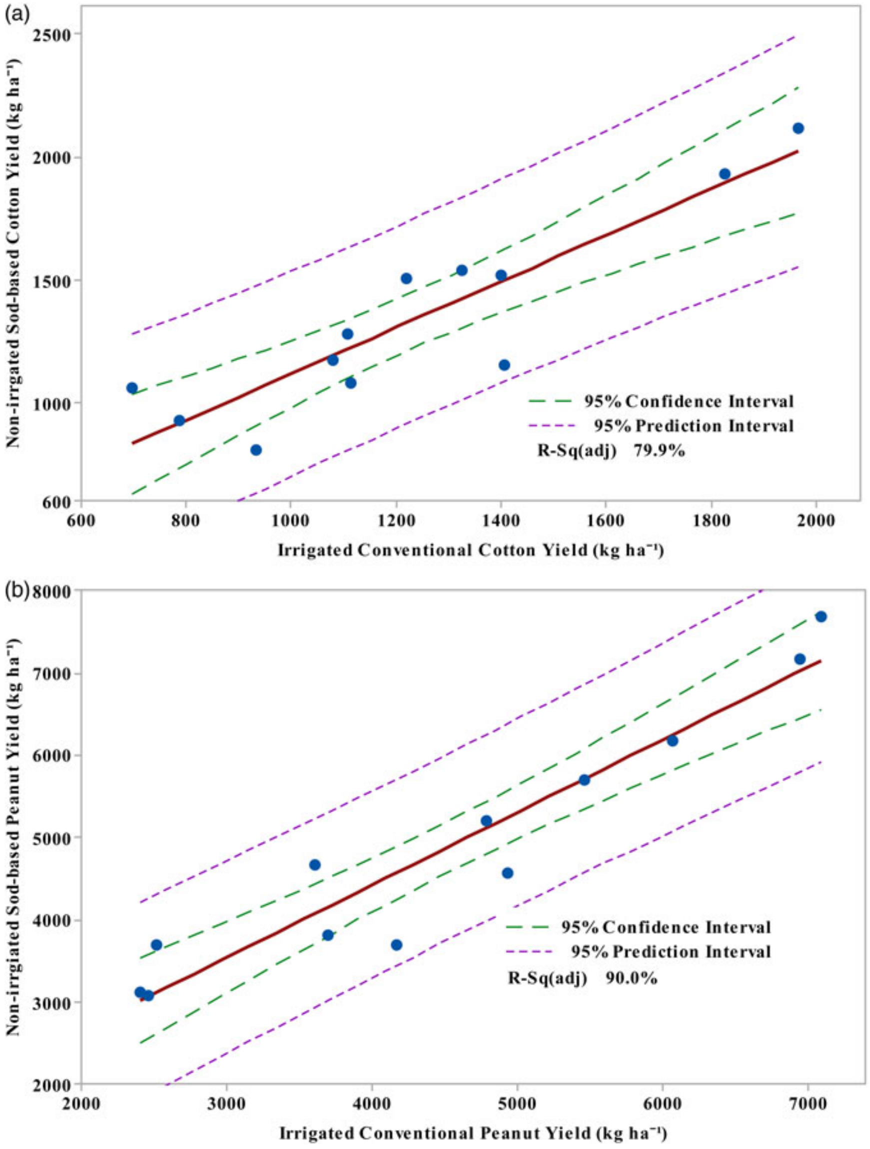

Figure 4. (a) Linear regression fits of cotton yield in a non-irrigated SBR (bahiagrass–bahiagrass–peanut–**cotton**) and ICR (peanut–**cotton**–cotton). (b) Linear regression fits of peanut yield in a non-irrigated SBR (bahiagrass–bahiagrass–**peanut**–cotton) and ICR (**peanut**–cotton–cotton).

April and mid-May. Bahiagrass was killed in the fall of the second growing season with glyphosate [*N*-(phosphonomethyl) glycine; 1.1 kg a.i. ha^{-1}]. After cotton and peanuts were harvested in the fall (late September to October), all plots (except those in 1st year bahiagrass) were planted with seed oats (*Avena sativa* L) as winter cover crop. Oats were planted using a Great Plains no-till drill at a seeding rate of 67 kg ha^{-1}. The cover crop was fertilized using a 34-0-0 at 141 kg ha^{-1} (48.4 kg N ha^{-1} ammonium nitrate) and killed in early spring using glyphosate (1.1 a.i. kg ha^{-1}).

Root mass measurements

Root mass of oats in both the SBR and ICR was measured at different depths to compare root development in the two rotation systems. Two soil cores (each 1 m in length and 0.1 m in diameter) were taken in each plot in February 2010. The core was sectioned into the following depth increments: 0–15, 15–30, 30–50, 50–70 and 70–95 cm. Each section was submerged briefly in tap water. A 0.5 mm^2 sieve was used to separate the roots from the soil suspension. The roots were further washed clean using tap water, oven-dried at 60°C till constant weight (approximately 24 h) and then weighed. Results are means of three replicates.

Simulated long-term, probabilistic irrigation demands

Parallel to the field data analysis, simulations were run to estimate the water-saving potential of SBR over a wide

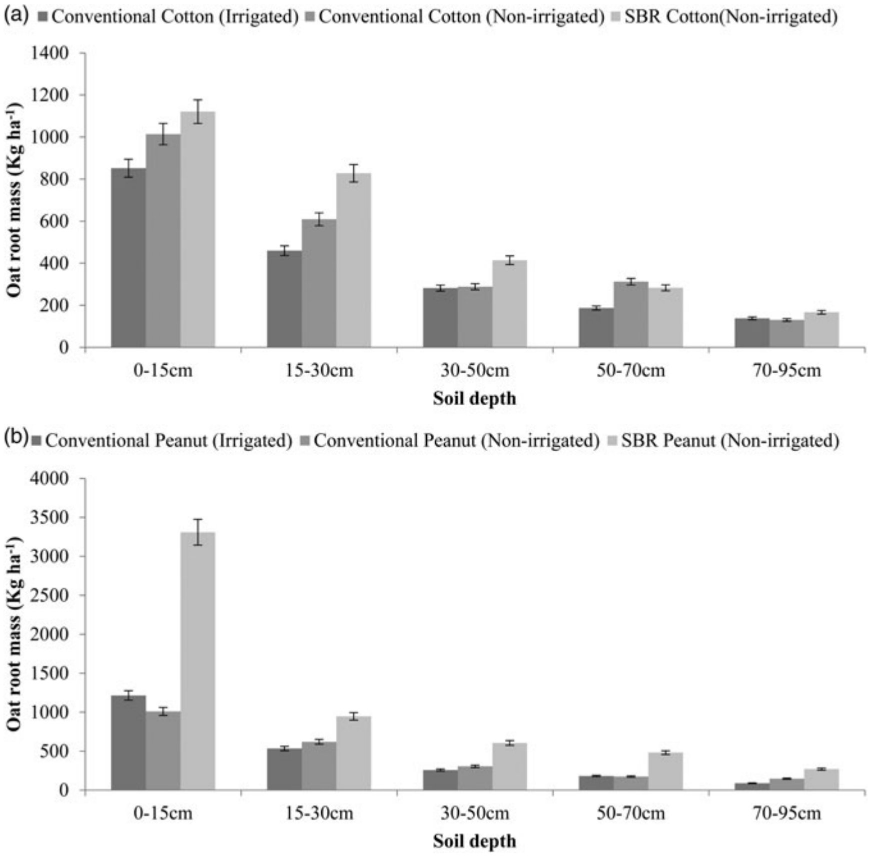

Figure 5. (a) Root mass of *A. sativa* L (oats), measured in February 2010, in ICR (peanut–**cotton**–cotton), non-irrigated conventional rotation (peanut–**cotton**–cotton) and non-irrigated SBR (bahiagrass–bahiagrass–peanut–**cotton)**. Oats was grown as a cover crop following cotton in both the rotation systems. Crop in bold indicates crop that preceded oats in the two rotation systems. Error bars represent 95% C.I. (b) Root mass of *A. sativa* L (oats), measured in February 2010 in an ICR (**peanut**–cotton–cotton), non-ICR (**peanut**–cotton–cotton) and non-irrigated SBR (bahiagrass–bahiagrass–**peanut**–cotton). Oats was grown as a cover crop following peanut in both the rotation systems. Crop in bold indicates crop that preceded oats in the two rotation systems. Error bars represent 95% C.I.

range of soil type and weather conditions during the growing season. The WaterFootprint tool on www.AgroClimate.org[23], a dynamic, web-based tool for comparing water footprint of agricultural systems was employed to compute irrigation water demand.

The WaterFootprint tool estimates consumptive water use, separately for irrigation water and rainfall, relative to crop production for specific agricultural practices. The tool retrieves and formats weather data from the Global Historical Climatology Network (GHCN-Daily;[24]) for selected growing seasons. A crop growth and hydrology model (Soil and Water Assessment Tool; SWAT) was used to estimate yield and a variety of water balance components (infiltration, runoff, deep percolation, evapotranspiration) for cotton, corn and soybean for selected locations from field experiment sites in Bushland, TX, Mead, NE and Port Royal, VA in the USA for both dryland and irrigated systems[23]. This model has been consistent in matching measured values of ET and yield for these locations[23]. The simulations of crop growth and hydrology in the WaterFootprint tool make use of the Environmental Policy Integrated Climate (EPIC) crop growth model[25] within the framework of the SWAT[26]. User inputs are simplified to include: (1) location, (2) crop, (3) planting and harvest dates, (4) yield as input or simulated, (5) soil texture, root zone depth, soil organic matter, (6) tillage, (7) irrigation management and (8) fertilizer application. Soil properties are based on the HC27 generic/prototypical soil profiles that have been used for global crop modeling applications[27]. The HC27 soil descriptions give three choices each of maximum root zone depth (60, 120 and 180 cm), soil texture (sandy, silty and clayey) and organic matter content in the top soil (1.4, 1.0 and 0.4%). These settings for rooting depth, soil types and organic matter are reasonable options for the Southeast USA and represent the region adequately.

The variable adjusted in the model to distinguish between SBR and ICR was maximum rooting depth. To simulate crops in the ICR, rooting depths were set as 'shallow' and set to a maximum depth of approximately 2 ft (60 cm). This depth is greater than the typical soil

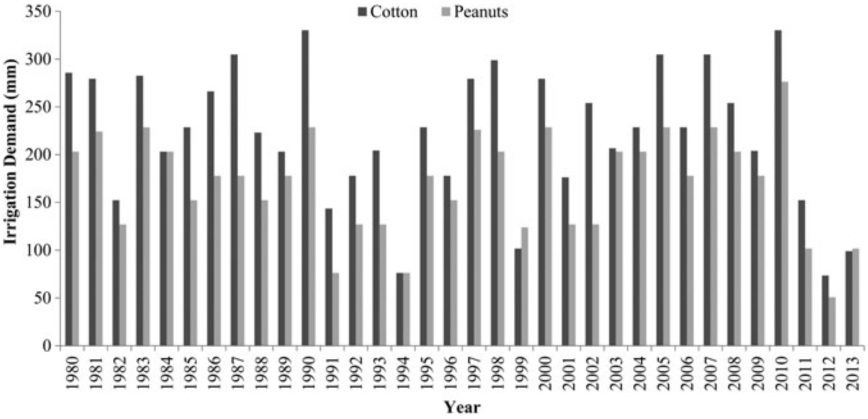

Figure 6. Model simulated irrigation demands from 1980 to 2013 for cotton and peanut in an ICR (peanut–cotton–cotton) on a shallow sand.

compaction zone depth found in the region at 45 cm or less[7,8]. However, in order to make conservative estimations of water savings that can be expected from an SBR system, a greater rooting depth was set for crops in the ICR. Roots of annual crops following bahiagrass follow the root channels created by the grass, so that root biomass is increased 30–40% compared with annual crops in non-bahiagrass rotations[8,14]. Since the model cannot account for this additional root growth, a practical way to compensate for it was to set SBR crop rooting depth to 'deep' at 180 cm. This value is supported by previous reports of cotton and peanuts growing under water stress[28–30]. At maturity, for both systems, the model computed root biomass as 20% of total plant biomass. The model simulates root growth to the specified maximum depth, but if there is some plant stress from water or nutrient deficiencies the model simulates less root biomass. Sand, silt and clay soil textures were evaluated using the model. Irrigation was set to begin at a plant water stress factor of 0.5 for both rotation systems. This is a reasonable value that a farmer in the Southeast would adhere to in order to avoid yield loss. An empirical Weibull cumulative distribution function (CDF) was selected[31] as a best fit for historical simulated irrigation data. We used the Weibull CDF instead of a normal probability distribution because the latter was not accurate enough at the upper tail of the data where the more extreme droughts occur. The statistical package Minitab (Release 17.0, 2010) was used to evaluate all possible CDF distributions of the data[32]. Irrigation water demand data generated for ICR was developed probabilistically to estimate the differences in water demand between ICR and SBR.

Results

Total water applied (irrigation plus precipitation) was compared against SWAT model estimates of actual evapotranspiration (AET) for well-watered cotton and peanut (Figs 1 and 2). Small differences in crop yield were observed between cotton and peanut in the ICR and SBR (Fig. 3a and b). Mean yield of cotton in SBR was 102 kg ha^{-1} higher than ICR (1339 and 1237 kg ha^{-1}; $P < 0.05$, paired t-test). Cotton yield differences between the two systems were not significant even in dry years except in 2007 when cotton yield in SBR was 252 kg ha^{-1} less than ICR ($P < 0.05$). Mean yield of peanut were 365 kg ha^{-1} higher in SBR than ICR (4874 and 4509 kg ha^{-1}; $P < 0.05$, paired t-test) but SBR yields were lower in dry years (2007 and 2008).

A regression analysis was used to test the association between cotton and peanut yields in SBR and ICR (Fig. 4a and b). For this analysis the yield in SBR was treated as the dependent variable and yield in ICR was treated as the covariate. The regression fits and the plotted prediction interval are an indication that each pair of new observations are likely to be very close to each other 95% of the time with yield in the SBR predicted to be slightly higher on average. Most of the data also fall well within the 95% confidence interval (C.I.) of the mean response line. Residual fits of these regressions against year to represent time order were not significant and when added as a variable, 'year' was not significant. The upward time trend in yields that occur in both the ICR and SBR is likely to be explained by improved management and other biophysical factors such as overall improved soil quality, crop varieties and later year increased rainfall amounts which would impact both systems more or less equally.

Root mass of oats following cotton or peanut in the SBR indicate an overall greater mass at each depth analyzed than those following cotton and peanut in the ICR (Fig. 5a and b). The simulated, historical irrigation demand for cotton and peanut in the ICR (shallow rooted) on a sandy soil at Quincy, FL indicates the water demand in this system (Fig. 6). The simulated irrigation demand for cotton and peanut in the SBR (deep rooted) was zero. The CDF plots illustrate the model demand data which fits for the irrigated cotton and peanut in the

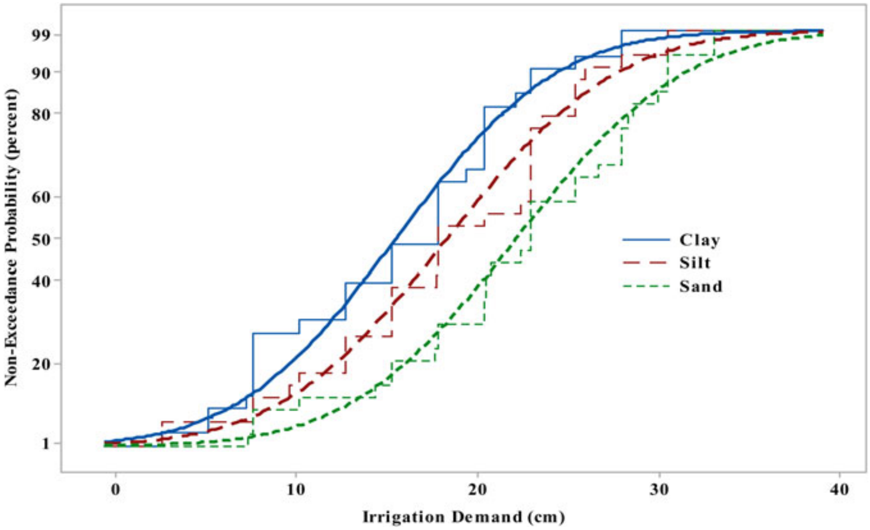

Figure 7. Empirical Weibull CDF fits of model simulated irrigation demand data for cotton in sand, silt and clay in an ICR (peanut–**cotton**–cotton).

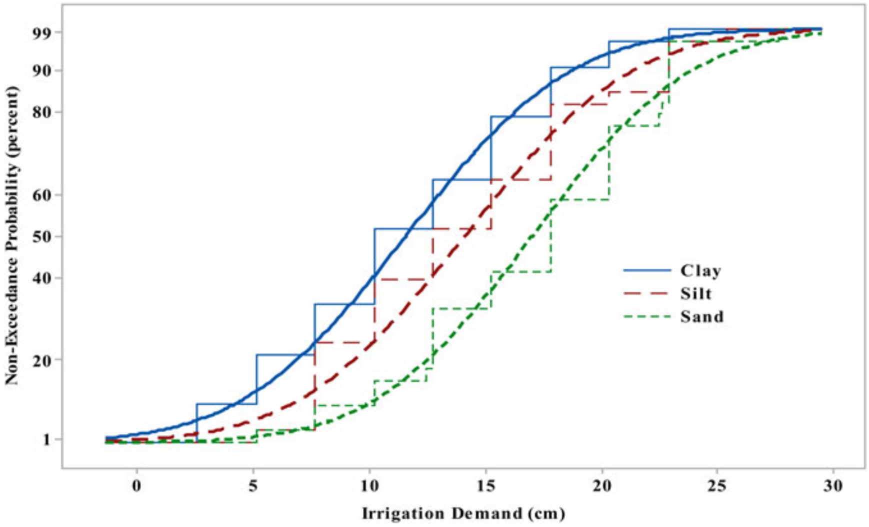

Figure 8. Empirical Weibull CDF fits of model simulated irrigation demand data for peanut in sand, silt and clay in an ICR (**peanut**–cotton–cotton).

ICR by soil type (Figs. 7 and 8). Irrigation demand exceedance probabilities for median dryness (50th percentile), 10% drought and 1% extreme drought indicate the increased irrigation demand of crops in ICR with increasing drought intensity and increasing percentage of silt and sand (Table 1). Crops in the SBR represented by deep roots showed essentially no increase in irrigation demand with increased drought intensity. Results indicate a substantial irrigation demand reduction with SBR.

Discussion

Simulation results for a 34 yr period helped to confirm that as growing season rainfall becomes less plentiful, crops in a SBR system consistently have substantially lower irrigation requirements than those in ICR. The simulations, similar to field observations, indicate resilience of the SBR system to drought. The model results further indicate that with increasing silt and sand fractions in the soil, probability of water savings of the SBR system increases. The SWAT is typically used for landscape-scale analysis and hence has certain limitations. However, the crop growth and soil water balance process descriptions are effective at capturing the field scale hydrology and plant development since these processes are based on the EPIC crop model that was developed for field scale crop modeling.

The simulation results are in agreement with 12 yr of experimental field data in Quincy, FL on a soil consisting of

Table 1. Forecasted water savings from SBR based on irrigation demand of cotton and peanut in an ICR (peanut–cotton–cotton). Table shows irrigation demand exceedance probabilities under conditions of median dryness (50%), drought (10%) and extreme drought (1%) for crops in an ICR under clay, silt and sand. Crop irrigation demand for ICR presented here is the water savings achieved in a non-irrigated SBR.

Soil type	Exceedance probability (%)	Irrigation demand (cm)	95% C.I. (cm)
Peanut			
Clay	50	11.2	9.1–13.2
Clay	10	19.1	16.0–22.4
Clay	1	25.9	20.8–31.8
Silt	50	14.0	11.9–16.0
Silt	10	21.3	18.8–24.4
Silt	1	27.4	23.4–32.3
Sand	50	17.0	15.5–19.1
Sand	10	23.6	21.6–25.9
Sand	1	28.4	25.1–32.3
Cotton			
Clay	50	15.0	12.7–17.8
Clay	10	24.4	21.1–28.4
Clay	1	32.5	26.9–39.4
Silt	50	18.0	15.5–20.6
Silt	10	27.7	24.1–31.5
Silt	1	35.6	30.0–42.2
Sand	50	22.1	19.8–24.6
Sand	10	31.0	27.9–34.3
Sand	1	37.6	33.0–42.7

near surface sands and clay at depths below 45 cm. On average an 8% increase in crop yield could be expected from SBR over ICR. Rainfall data indicated relatively greater number of agricultural ‘droughts’ or low growing season rainfall amounts, the lowest of which occurred in the years 2007, 2008 and 2010. In these three dry years, cotton AET estimates are likely to have been slightly overestimated because irrigation water was more frugally applied and distributed over the season than what was computed by the model as a ‘well-watered’ condition. Based on observed yields for these years, cotton did not appear to have been water stressed. In most years the total water applied (rainfall + irrigation) was in excess of the AET estimates indicating that crops in the ICR were well-watered.

Depending on soil type, the expected water savings of crops in the SBR during a moderate 10% chance drought would range from 18 to 30.5 cm of water. As soil texture changes to increasing sand content with less inherent water-holding capacity, the water-saving potential of the SBR system increases. Further field research is warranted on deep sand soils to verify these results.

The periods of high irrigation demand (growing season May through October) are also coincident with reduced streamflows and availability of water in the Southeast USA, further increasing the significance of the SBR system. The reduced operational costs of irrigation could be computed directly based upon the amount of water that would no longer need to be applied or pumped. In situations where well water is used these costs will vary depending on the depth of the pumping water level in the supply well and the operating pressure of the irrigation system. Operational cost savings would generally be based on the unit energy costs of the fuel used to operate pumps, labor and maintenance of the irrigation system. The range of savings could be between US$79 and 400 per hectare depending on soil type, severity of drought and other on-farm production factors (unpublished results).

Conclusions

Innovative agricultural management solutions are needed to ensure sustainability of water resources amidst intensifying competition for water resources. Climate change characterized by elevated temperatures, carbon dioxide, and ozone, and variable precipitation pose strong challenges to the sustainable intensification of agriculture. Climate modeling indicates that there will be an increase in areas experiencing droughts as well as an increase in heavy precipitation events[33,34]. Heavy precipitation leads to rapid soil erosion and runoff while low precipitation leads to inadequate availability of water during key crop production phases. The Southeast USA is particularly vulnerable to these extreme events with future projections indicating 20–25% less precipitation in this region[35]. Crop producers try to adapt to these uncertainties by moving toward irrigated farming placing huge demands on River basins in the region. A growing population further complicates the issue since agriculture has to compete with urban and industrial water use. Regulation of agricultural water use and high cost and energy demands associated with irrigated crop production may compel farmers to resort to dryland farming, potentially risking productivity.

This study supports SBR as a management system that can increase productivity, enhance sustainability of water resources and provide substantial economic benefits to producers. Using conservation tillage, cover crops and precision agricultural technologies are useful climate change adaptation strategies that could achieve water savings to varying extents[36]. However, SBR buffers climate variability and changing crop water demand by improving soil quality and structure. This system affects soil quality in two ways. At shallow depths (top 15–20 cm) it increases water infiltration and water-holding capacity through increased organic matter. At deeper depths the annual crops following bahiagrass take advantage of their deep and extensive root systems to overcome soil compaction and utilize water available at those depths. This system further mitigates potential economic risk owing to climate variability by utilizing only half the producer’s acreage for cash crop production. Although this could be perceived as a system with low returns, in a less favorable year (drought or other extreme weather events), this translates into a much lower loss as compared with that in a traditional rotation with only cash crops. Thus cropping system resilience afforded by SBR is especially significant in the context of climate variability and the prospect of having to farm row crops in the Southeast with limited access to water. Although there are fewer years of cotton and peanut production in the SBR system as compared with ICR, enhanced crop performance and savings achieved due to reduced irrigation water demand and other resources makes this system more economically profitable. The operational cost savings due to reduced irrigation needs results in direct savings for the producer. The reduced irrigation demand of this system, up to 100%, also has significant water resource sustainability and economic benefits if applied on basin-wide scales especially where irrigation may already be impacting water supplies and environmental water flows as pointed out previously in this paper.

Further research is needed to confirm the breadth of SBR performance under different climatic and soil conditions and topography to facilitate informed decision-making on the part of producers and policy-makers.

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