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ORIGINAL PAPER

Long-term simulations of site-specific irrigation management for Arizona cotton production

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Abstract
Engineering technologies for site-specific irrigation management (SSIM) have already been developed for applications in precision irrigation. However, further studies are needed to identify scenarios where SSIM leads to better agronomic outcomes than conventional uniform irrigation management (CUIM). The objective was to conduct a long-term simulation study to compare SSIM and CUIM given spatial soil variability at the Maricopa Agricultural Center (MAC) in Arizona. More than 500 surface soil samples were collected across a 730-ha area of the MAC from 1984 to 1987. A more detailed soil data set was more recently obtained across a 5.9-ha area at a MAC location designated for SSIM studies. Ordinary kriging was used for spatial interpolation of soil hydraulic properties within 10 m × 10 m zones across the MAC, and 11 field parcels with an area of approximately 60 ha were delineated on the MAC quarter sections. Using an agroecosystem model, simulations of cotton production at the zone level with a 30-year weather record were conducted using a field-tested algorithm to optimize irrigation schedules for SSIM and CUIM. Long-term seed cotton yield, irrigation requirements, water use efficiency, and marginal net return for SSIM and CUIM strategies were often not different ($p > 0.05$). Differences in seed cotton yield and irrigation requirements among the tested irrigation strategies were less than 11% and 6%, respectively, and within the typical range of model error. Most soils on the MAC have enough available water holding capacity to sustain cotton production at full potential with weekly CUIM, and advantages of SSIM were not consistently demonstrated by the simulations.

Introduction

Site-specific irrigation management (SSIM) technologies on mechanical-move sprinkler irrigation systems can adjust water applications according to spatial variability in soil or crop conditions. Generally, there are two methodologies for controlling water applications site specifically: (1) speed-controlled SSIM (SC-SSIM) where the travel speed of the irrigation machine is varied based on its position in the field and (2) zone-controlled SSIM (ZC-SSIM) where specialized valves, positioning equipment, and other hardware are incorporated to vary application rates from individual nozzles or groups of nozzles based on prescription maps or sensor feedback. Both approaches permit variable water applications in the direction of travel, while only the latter method permits rate adjustments along the length of the machine. Options for SC-SSIM are often included as a standard feature in modern irrigation control panels, but Evans et al. (2013) estimated that less than 200 of 175,000 machines in the U.S. were equipped with ZC-SSIM technology. Some existing machines were designed only for conventional uniform irrigation management (CUIM) and have no ability to vary water applications spatially. Although SSIM technology has been available for many years, it has not been widely adopted due to (1) lacking evidence on its ability to conserve resources or improve profit, (2) deficiencies in tools to support in-season crop monitoring, management zone delineation, and decision making, and (3) lacking technical support to maintain SSIM systems and ensure proper functionality (Evans and King 2012; Evans et al. 2013; O'Shaughnessy et al. 2016; Sadler et al. 2005). These limitations must be clarified and overcome before SSIM technology will have a meaningful impact on irrigated agriculture.

Although great efforts have been made to develop engineering technologies for SSIM (Haghverdi et al. 2016; Kranz et al. 2012; Romero et al. 2012; O'Shaughnessy et al. 2016), only a few studies have comprehensively compared

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agronomic outcomes from SSIM versus CUIM. For example, King et al. (2006) conducted a 2-year field study to compare the effects of SSIM and CUIM on potato (*Solanum tuberosum* L.) yield and quality with irrigation management based on soil water content measurements. Potato yield and water use efficiency were increased by 4% with SSIM, but neither were significantly different from results with CUIM ($p = 0.05$). They concluded that SSIM was not economically viable for their potato production system. Stone et al. (2015) conducted a 3-year study comparing SSIM and CUIM for peanut (*Arachis hypogaea* L.) production. Among treatments using the Irrigator Pro expert system to schedule irrigation by plot (i.e., CUIM) and by soil within plot (i.e., SSIM), no significant differences in peanut yield or water use efficiency were found ($p = 0.05$). Lu et al. (2005) conducted an economic evaluation of SSIM for maize (*Zea mays* L.) based on yield response variability among soil map units and irrigation rates (Sadler et al. 2002). Results demonstrated that SSIM led to higher net returns than CUIM, but they speculated that costs of the additional equipment required for SSIM would not be offset. Some have claimed that SSIM is a solution looking for a problem, meaning the engineering developments that make SSIM possible are not yet justified by a real need or benefit (Evans and King 2012; Evans et al. 2013).

Field studies are often limited to relatively small plot areas for a few growing seasons and may lack the spatial and temporal breadth for comprehensive analyses of SSIM. Agroecosystem models offer a relatively rapid and inexpensive option for evaluating SSIM for multiple fields and growing seasons. Nearly 30 years ago, Ritchie and Amato (1990) used CERES-Maize with 30 years of weather data in Michigan to evaluate SSIM for a 4.6-ha maize field with spatial variability in available water holding capacity (AWHC). The model simulated optimal maize yield with SSIM, and CUIM led to water deficit or wastage depending on the soil type used for irrigation management decisions. Nijbroek et al. (2003) used CROPGRO-Soybean with 25 years of weather data in Georgia to evaluate SSIM for a 9.9-ha soybean (*Glycine max* (L.) Merr.) field, which was divided into five management zones based on AWHC. Although SSIM was deemed the best management option for crop yield and net return (ignoring fixed costs), CUIM did not reduce net return by more than \$16 ha^{-1}, leaving little funds for additional equipment costs as required for SSIM. Al-Kufaishi et al. (2006) used a sugar beet (*Beta vulgaris* L.) model with 1 year of weather data to compare SSIM and CUIM for a 7.1-ha field in Germany. The SSIM scenarios were shown to reduce overapplication of water as compared to CUIM. Hedley et al. (2009) used a simple soil water balance model (without a crop growth simulation) to compare SSIM and CUIM for three growing seasons at two sites: a 53-ha maize field and a 156-ha pasture of ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.). The analysis showed that SSIM could reduce irrigation applications from 20% to 26% by making better use of stored soil water. All of these simulation studies were conducted for crops in humid regions, and no simulation analyses comparing SSIM and CUIM in an arid region were found in literature. Also, simulations studies have often used different approaches for automatic irrigation scheduling, and it is unclear whether the modeling approaches provide irrigation schedules that could be realistically implemented and field tested using modern irrigation equipment (Evans and King 2012). Finally, many of the fields evaluated in prior studies were relatively small, which may have limited the variability of spatial soil properties under consideration. Efforts are warranted to evaluate SSIM for field areas more typical for production-scale irrigation equipment using algorithms that have been thoroughly field tested for in-season irrigation scheduling.

In the low desert of central Arizona, traditional surface irrigation management is still routinely used, mainly due to existing infrastructure for delivery of Colorado River water to growers through irrigation district canals. However, adoption of modern overhead sprinkler irrigation systems is occurring, and local stakeholders are curious about the role of SSIM in the area. To establish initial estimates of SSIM efficacy for central Arizona, the objectives of this research were to (a) conduct a simulation study to contrast SSIM versus CUIM given spatial variability in AWHC across the Maricopa Agricultural Center and (b) assess the potential for SSIM to improve cotton (*Gossypium hirsutum* L.) yield, water use efficiency, and marginal net return as compared to CUIM.

Materials and methods

Study site

The study site was located at the University of Arizona's Maricopa Agricultural Center (MAC) near Maricopa, Arizona (33.073° N, 11.984° W, 360 m above sea level). Cotton is a primary commodity crop in central Arizona, typically grown from April through September during the hot and dry summer conditions. Since 1987, an Arizona Meteorological Network (AZMET; http://ag.arizona.edu/azmet/) station has been operational at the site. Based on data from 1987 to 2016, maximum daily air temperature regularly exceeded 38 ° C in July and August, and minimum daily air temperature often did not fall below 27 ° C. Average precipitation during the cotton growing season was 70 mm, while average seasonal short crop reference evapotranspiration (ET_o) was 1335 mm. Thus, irrigation is a necessity for cotton production.

Because traditional surface irrigation is commonly used to meet crop water requirements in central Arizona, a network of concrete-lined canals is used to deliver water to fields covering more than 800 ha at the MAC. Although irrigation is critical for all field investigations at the MAC, only a few studies have utilized mechanical-move overhead sprinkler irrigation systems (Bronson et al. 2017; Haberland et al. 2010; Kostrzewski et al. 2003). The coverage area of these systems was less than 1.5 ha, and none were capable of ZC-SSIM. In 2014, a six-span lateral-move sprinkler irrigation system with capability to irrigate 5.9 ha was installed at the MAC, and commercial equipment for ZC-SSIM was added 1 year later (Thorp et al. 2017). However, there are currently no production-scale mechanical-move systems capable of irrigating more than 6 ha at the MAC. Directly south of the MAC, the Ak-Chin Indian Community is the greatest adopter of mechanical-move irrigation systems in the area. They manage more than 40 machines, mostly lateral-move sprinklers with central feeding from concrete-lined canals and two laterals extending 400 m in opposite directions. Such machines often irrigate 60 ha or more. While more expensive than central-pivot systems, this style of irrigation system is easily adapted to the existing canal infrastructure and rectangular field areas in central Arizona. Therefore, the analysis presented herein was tailored for this type of lateral-move irrigation system. Furthermore, because laser leveling is commonly practiced to promote uniformity of surface irrigation in central Arizona, most fields exhibit nearly uniform topography. Thus, field topography was not considered in the analysis.

The MAC land area was divided into 11 parcels for a simulation analysis to compare SSIM and CUIM, considering variability in measured soil properties. Ten of the parcels were established based on the quarter-sectional areas at the MAC, using a digital orthophoto quadrangle (DOQ) as a reference for geographic coordinates (Fig. 1). The analysis areas for these parcels ranged from 53 to 60 ha (Table 1). Hypothetically, center-fed lateral-move irrigation systems capable of ZC-SSIM could be installed here, but do not currently exist. The remaining parcel (Parcel #6) was established at the location of the existing lateral-move irrigation system with ZC-SSIM at the MAC. The analysis area for this parcel was 6.3 ha.

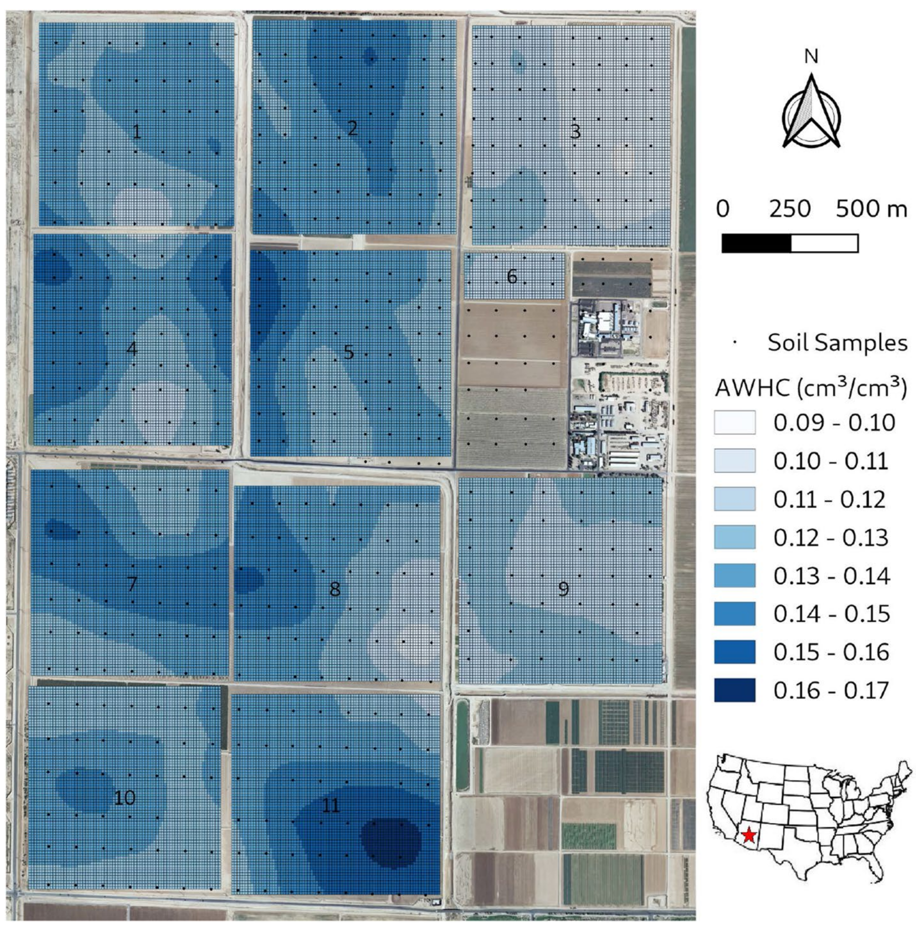

Fig. 1 Map of the Maricopa Agricultural Center with 11 parcels delineated for site-specific irrigation management via lateral-move overhead sprinkler irrigation systems. Each parcel was divided into 10 m × 10 m zones. Drained upper limit (DUL) and lower limit (LL) were computed centrally in each zone using ordinary kriging with data from 552 soil sampling locations, and available water holding capacity (AWHC, $cm^3\ cm^{-3}$) was computed as DUL minus LL

Table 1 Information on the 11 parcels delineated for long-term simulations of site-specific irrigation management at the Maricopa Agricultural Center. Each parcel was divided into 10 m × 10 m zones

Parcel	Soil data	# of zones	Area (ha)	MIN AWHC ($cm^3\ cm^{-3}$)	MED AWHC ($cm^3\ cm^{-3}$)	MAX AWHC ($cm^3\ cm^{-3}$)
1	Post	5400	54.0	0.131	0.161	0.177
2	Post	5925	59.3	0.128	0.169	0.180
3	Post	5913	59.1	0.091	0.102	0.127
4	Post	5694	56.9	0.125	0.158	0.173
5	Post	5624	56.2	0.129	0.151	0.173
6	Post	629	6.3	0.113	0.119	0.131
6	Thorp	629	6.3	0.123	0.133	0.137
7	Post	5548	55.5	0.131	0.153	0.162
8	Post	5472	54.7	0.111	0.169	0.177
9	Post	5700	57.0	0.128	0.124	0.142
10	Post	5325	53.3	0.138	0.144	0.166
11	Post	5698	57.0	0.125	0.168	0.179

The zones with minimum (MIN), median (MED), and maximum (MAX) available water holding capacity (AWHC) were identified for each parcel

MAC soil data

After the MAC was established in the early 1980s, efforts immediately focused on mapping the soil texture variability across the farm (Post et al. 1988; Suliman 1989). From May 1984 to January 1987, researchers bored soil samples to an approximate depth of 1.0 m at 552 locations across 730 ha at the MAC. Sampling locations were established on a rough grid with about 130 m between sampling points (Fig. 1). A rapid analytical procedure based on a laser-light scattering technique (Cooper et al. 1984) was used for texture analysis of all 552 soil samples. To verify the accuracy of the analytical method, 21 samples were additionally analyzed for soil texture using the pipette and hydrometer method of Day (1965). Cooper et al. (1984) reported Pearson's correlation coefficients (r) of 0.85 and higher for the linear relationship between particle sizes determined by the two methods. Three soil series (Casa Grande, Trix, and Shontik) were mapped on the MAC, and surface soil textures were mainly sandy loam, sandy clay loam, and clay loam. Detailed data from the MAC soil mapping effort can be found in the dissertation by Suliman (1989). Hereafter, this soil data set will be called the "Post" soil data (Post et al. 1988).

More recently, a soil mapping effort with greater spatial detail was conducted on Parcel #6 after construction of the lateral-move ZC-SSIM system there (Fig. 2). In 2016 and 2017, soil samples were collected at 160 locations across the 5.9-ha field area using a tractor-mounted Giddings soil sampler (model 25-TS, Giddings Machine Co., Windsor, Colorado). The sampling locations were mapped with a real-time kinetic (RTK) global positioning system (GPS) receiver with centimeter-level horizontal accuracy (Model #5800, Trimble Inc., Sunnyvale, California). Soil sampling efforts typically coincided with other field activities, including installation of access tubes for neutron moisture meters and soil sampling for pre- and post-season nitrate analysis. A soil boring tube was used to collect cylindrical soil samples (0.04-m diameter × 0.4-m depth) at five incremental soil profile depths centered at 0.2, 0.6, 1.0, 1.4 and 1.8 m. Samples were ground, oven dried, and weighed. Soil bulk density

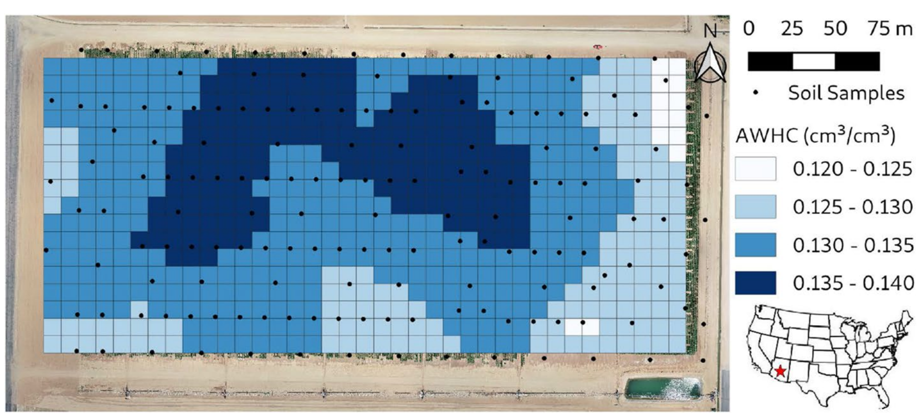

Fig. 2 Map of Parcel #6 where a lateral-move overhead sprinkler irrigation system capable of zone-controlled site-specific irrigation management is currently installed. The parcel was divided into 10 m × 10 m zones. Drained upper limit (DUL) and lower limit (LL) were computed centrally in each zone using ordinary kriging with data from 160 soil sampling locations, and available water holding capacity (AWHC, $cm^3\ cm^{-3}$) was computed as DUL minus LL

was calculated from the dry weight and estimated sample volume. Soil texture analysis was conducted on all samples using the hydrometer method of Gee and Bauder (1986). Hereafter, this soil data set will be called the "Thorp" soil data. In comparison to the Post soil mapping effort in the 1980s, the Thorp data was collected 3 decades later by different people using different equipment and methods, and the soil texture analysis methodology was also different. However, both approaches predominately characterized the soil texture in the vicinity of Parcel #6 as sandy loam.

Soil texture data from both soil mapping efforts were input to the Rosetta pedotransfer functions to calculate physical properties (Zhang and Schaap 2017). For the Parcel #6 data, the sand, silt, and clay percentages from soil texture analysis and the field-average bulk density per profile layer depth were input to Rosetta. Mean bulk density was used to account for uncertainty in the bulk density data arising from issues with soil sampling (e.g., compaction from the soil boring equipment, loose soil falling back in the hole, and other sampling errors). For the Suliman (1989) data, only sand, silt, and clay percentages were input to Rosetta. Outputs from the Rosetta model included the lower limit, drained upper limit, saturated soil water content, and saturated hydraulic conductivity of each soil sample.

For purposes of the simulation study, each of the 11 parcels was subdivided into 10 m × 10 m management zones. Higgins et al. (2016) determined that the minimum management scale for a commercial ZC-SSIM system on a central pivot in Benton County, Washington was 23 m. Though such studies have not been conducted for the ZC-SSIM lateral-move machine at the MAC, visual evidence has suggested that the machine was spatially accurate to within a few meters. Furthermore, the ZC-SSIM lateral-move system at the MAC currently uses bubbler pads for in-season cotton irrigation, with drop hoses spaced 1.0 m and centered between cotton rows. This has provided a wetted diameter of less than 0.5 m for each nozzle, leading to highly accurate placement of water using ZC-SSIM equipment and prescription maps. No effort was made to reduce management zone numbers by clustering zones with similar characteristics (Haghverdi et al. 2016). Instead, because a main objective was to compare the performance of SSIM with CUIM, the analysis was scaled based on characteristics of the known ZC-SSIM irrigation system at the MAC. On the other hand, it was not reasonable to evaluate land areas larger than what could be irrigated by a typical production-scale overhead irrigation system. Therefore, the parcels of approximately 60 ha (Table 1) served as the maximum spatial management unit, and each parcel was further subdivided into 10 m × 10 m management zones, which served as the minimum spatial management unit. The standard deviations of AWHC at the scales of the 10 m × 10 m management zones and the 60-ha parcels were, respectively, 0.012 and 0.009 $cm^3 cm^{-3}$. This suggested that greater AWHC variation existed at the finer spatial scale and further justified the need to conduct SSIM analyses at the sub-parcel level.

Empirical semivariograms were computed from the geospatial data, including soil texture and soil hydraulic properties. Ordinary kriging was used to spatially interpolate these data at the central location of each management zone. Geostatistics were conducted using the "geoR" package within the R Project for Statistical Computing software (https://www.r-project.org/).

Simulations

The Decision Support System for Agrotechnology Transfer (DSSAT) Cropping System Model (CSM; ver. 4.7.2.001) was used to analyze seed cotton yield (fiber + seed), evapotranspiration (ET), and irrigation requirements for all the 10 m × 10 m management zones within the 11 parcels. Specifically, the CSM-CROPGRO-Cotton model was implemented, which uses mass balance principles to simulate carbon, nitrogen, and hydrologic processes and transformations that occur in an agroecosystem. Simulations of cotton development proceed through a series of stages based on photothermal unit accumulation from planting to harvest. Light interception is simulated based on an elliptical hedgerow canopy, and potential carbon assimilation is computed from leaf-level biochemistry equations with growth and maintenance respiration deducted. The model calculates stress effects from deficit soil water and nitrogen conditions, which further reduce the carbohydrate available for simulated plant growth. Assimilated carbon is partitioned to various plant parts, including leaves, stems, roots, bolls, and seed cotton. Water deficits are simulated when the potential demand for water lost through plant transpiration is higher than the amount of water supplied by the soil through the simulated root system. The amount of water supplied by the soil is a function of AWHC, as defined by model inputs for drained upper limit and lower limit. As reported by Thorp et al. (2014b) and DeJonge and Thorp (2017), the Walter et al. (2005) standard algorithm for ET_o calculations was recently added to the model as an ET simulation option, and DeJonge and Thorp (2017) further updated the model to include a dual crop coefficient ET method with basal crop coefficients (K_{cb}) estimated from model-simulated LAI. Inclusion of this ET algorithm made the model more relevant for irrigation scheduling purposes (Thorp et al. 2017). The model simulates a layered, one-dimensional soil profile with a tipping-bucket method for water redistribution and algorithms for calculating soil and plant nitrogen balances. Additional details about CSM-CROPGRO-Cotton can be found in Jones et al. (2003) and Thorp et al. (2014a, b, 2017).

The simulation analysis was conducted using 30 years of weather information from 1987 to 2016. Weather data were obtained from the AZMET station at the MAC, which provided daily solar irradiance (MJ m^{-2}), wind speed (km day^{-1}), precipitation (mm), and minimum, maximum, and dew point air temperatures (°C). Cultivar coefficients were specified as reported in Thorp et al. (2017), except for minor adjustments to three parameters (i.e., maximum leaf photosynthesis rate (LFMAX), 1.378 mg CO_2 m^{-2} s^{-1}; specific leaf area with standard growing conditions (SLAVR), 138.9 cm^2 g^{-1}; maximum fraction of daily growth that is partitioned to bolls (XFRT), 0.772). Two evapotranspiration parameters were also recalibrated prior to the present study [i.e., K_{cb} shaping coefficient (SKC), 0.51; maximum K_{cb} (KMAX), 1.225], and soil profile data for root growth factors (SRGF), bulk density (SBDM), and organic carbon content (SLOC) were updated. Adjustments to the model parameterization were based on improvements to the simulations after the report by Thorp et al. (2017). Soil hydraulic parameters were specified with the spatially interpolated data for each management zone.

To establish realistic initial values for soil water content in each 10 m × 10 m management zone, preliminary simulations were conducted using the soil data for each management zone with the management, weather, and cultivar data from the 2015 cotton simulations reported by Thorp et al. (2017). The final soil water content values for each management zone after simulating the 2015 cotton season were used to initialize the model for all simulations of that management zone in this study. Other methods for establishing initial soil water content values were tested (e.g., computing initial conditions relative to soil water limits or fixing initial conditions identically for all simulations). However, these approaches led to patterns in the simulation results that were thought to be impacted by the initial conditions themselves. Therefore, initializing the soil water content site specifically based on simulations of a full cotton growing season was thought to provide a more realistic representation of spatial variation in soil water content, which might exist at the beginning of a given Arizona cotton growing season.

All simulations were initiated on day of year (DOY) 1 (1 January) each year, which permitted an additional 3 months of simulations for further initialization of the soil water and nutrient state variables. Cotton planting and harvest were simulated on DOY 109 (19 April) and DOY 294 (21 October) in each year. A total nitrogen fertilization rate of 168 kg N ha^{-1} was simulated uniformly for each management zone in four even splits, occurring on DOY 137 (17 May), DOY 159 (8 June), DOY 172 (21 June), and DOY 186 (5 July). Naturally, the day of month for each DOY was 1 day later in leap years.

Irrigation for each management zone in each year was based on the methodology of Thorp et al. (2017), who developed and field tested an approach for in-season irrigation scheduling based on CSM-CROPGRO-Cotton simulations. Following common practices for Arizona cotton production, irrigation management was sectioned into three distinct timeframes: (1) pre-season irrigation to raise the soil water content and fill the soil profile prior to planting cotton, (2) post-planting irrigation used to emerge the cotton crop and reduce cotyledon breakage due to soil crusting, and (3) weekly in-season irrigation to meet ET demands and reduce water stress. Total pre-season irrigation was calculated as the amount of water required to fill the upper 120-cm soil profile depth to the drained upper limit on DOY 86 (27 March). This amount was applied over 6 days from DOY 81 (22 March) through DOY 86 (27 March) and could vary based on simulated site-specific soil conditions at that time. Following pre-season irrigation, 23 days were allowed for surface soil drying to permit field entry for cotton planting on DOY 109 (19 April). Irrigation to emerge the cotton crop and reduce soil surface crusting was applied on a fixed schedule over a 27-day period. From DOY 110 (20 April) to DOY 122 (2 May), irrigation was permitted every 3 days. From DOY 127 (7 May) to DOY 137 (17 May), irrigation was permitted every 5 days. Maximum irrigation amounts of 10 mm were permitted for each emergence irrigation event, except 20 mm was permitted on the day after planting (DOY 110) and 15 mm was permitted to reduce crusting on two dates around the expected time of emergence (DOY 116 and 119). If soil water depletion in the upper 30-cm soil profile depth became less than zero (i.e., a full profile) on a given day allotted for emergence irrigation, no further emergence irrigation was added on that day. Thus, emergence irrigation could possibly, but not necessarily, be site specific. The emergence irrigation schedule was based on two seasons of field data reported by Thorp et al. (2017) as well as experience from managing irrigation for three subsequent cotton growing seasons at the same field location. Iterative simulations were required to solve for the irrigation schedule given the constraints described above.

The schedule for in-season irrigation was solved uniquely for each management zone in each year using a similar iterative strategy. Based on field-tested practices (Thorp et al. 2017) and practical considerations for irrigating 60-ha parcels in the central Arizona environment, irrigation applications were permitted for four consecutive days on a weekly basis for 16 weeks from DOY 143 (23 May) to DOY 251 (8 September). For example, during the 1st week, irrigation was permitted on DOY 143 (23 May), DOY 144 (24 May), DOY 145 (25 May), and DOY 146 (26 May). Irrigation for the 2nd week could occur 7 days later: DOY 150 (30 May), DOY 151 (31 May), DOY 152 (1 June), and DOY 153 (2 June). The final (16th) week of irrigation was scheduled on DOY 248 (5 September), DOY 249 (6 September), DOY 250 (7 September), and DOY 251 (8 September). The possible irrigation DOYs were assumed identical among all simulation years. The irrigation schedule was solved on a weekly basis with the smallest incremental increase in irrigation assumed to be 5 mm, meaning 5 mm of irrigation was incrementally added to the 1st irrigation day of the week, then the 2nd, then the 3rd, then the 4th, followed by the 1st day again and so on until certain simulation output criteria were met. First, irrigation was added to account for evapotranspiration (less precipitation) that was predicted for the coming week. Second, additional 5 mm amounts were iteratively added until the model's two water stress factors, which can reduce plant growth and photosynthesis, had zero effect on the simulation for 8 days after the 1st day of weekly irrigation. Ensuring no stress for 8 days allowed time for the following week's irrigation to infiltrate the root zone and be available to the crop. Furthermore, the incremental additions to the weekly irrigation schedule were terminated if soil water depletion in the simulated rooting depth was less than zero (i.e., a full profile) on the 6th day after the first irrigation of the week. The weekly irrigation scheduling methodology was designed based on practical considerations for labor and water delivery, as encountered during previous field experiments.

This approach for solving the weekly irrigation schedule was based on the strategy developed and field tested by Thorp et al. (2017) for in-season cotton irrigation scheduling at the MAC. However, their study site was less than 6 ha, whereas a production cotton field may be 10 times larger. Further consideration was therefore required to ensure that the simulated irrigation schedules would not be limited by irrigation system capacity at production scales. The lateral move in Parcel #6, described by Thorp et al. (2017), can currently apply 5.1 mm of water, while traveling 175 m in 1.25 h or 140 m h^{-1}. Maximum weekly water use for cotton in central Arizona is about 75 mm at mid-season, and the value is naturally less during other times when ET demand is less. Applying 75 mm of water to Parcel #6 therefore requires 18.4 hours of time (75 mm ÷ 5.1 mm × 1.25 h = 18.4 h). A 60-ha quarter-sectional parcel is approximately 775 m long, so a similar machine would require 5.5 hours to apply 5.1 mm of water (775 m ÷ 140 m h^{-1} = 5.5 h) over 60 ha, and 80.9 hours (i.e., 3.4 days) would be needed to apply 75 mm of water (75 mm ÷ 5.1 mm × 5.5 h = 80.9 h). Thus, weekly irrigation events scheduled over 4 consecutive days per week is reasonable for production-scale cotton in Arizona, and the simulation results can be considered with confidence that the simulated irrigation schedules are relevant for Arizona cotton production and could be realistically administered by a modern lateral-move sprinkler irrigation system with SSIM capability. The realism of simulated irrigation schedules was previously suggested as a limitation in efforts to simulate SSIM (Evans and King 2012), particularly because many studies have ignored the timing limitations of irrigation machines and assumed that the systems could apply water instantaneously everywhere in the field.

Evaluations of CSM-CROPGRO-Cotton for multiple site years at the MAC have been previously reported by Thorp et al. (2014b, 2017). Because the present study incorporated a broader range of weather and soil information than previous studies, preliminary simulations were conducted to verify reasonable model responses among the range of soil and weather conditions. For 30 years of weather data, irrigation schedules were solved for three soils, which included the soils with minimum, median, and maximum AWHC over all 11 parcels in the Post data set. The daily amounts for these irrigation schedules were then adjusted from 40% to 140% of the recommended value in 10% increments, and simulations were rerun for each case. The simulations demonstrated that the model could appropriately respond by reducing both seed cotton yield and ET under water deficit stress and also by reducing seed cotton yield with excessive irrigation (Fig. 3). These preliminary simulations emphasized the ability of the

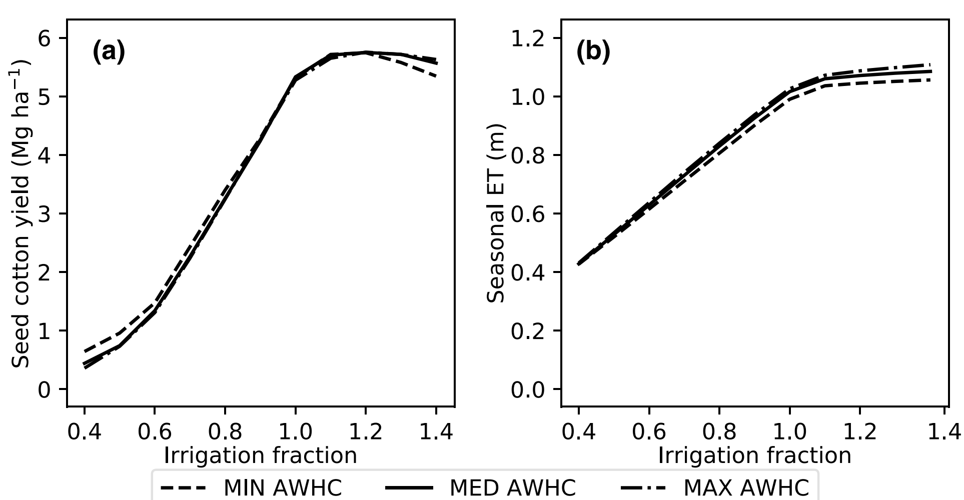

Fig. 3 Mean values of **a** seed cotton yield and **b** seasonal evapotranspiration (ET) over 30 years of weather data for the soils with minimum (MIN), median (MED), and maximum (MAX) available water holding capacity (AWHC) at the Maricopa Agricultural Center. Irrigation schedules were adjusted from 40% to 140% of recommended values to demonstrate the model response to both deficit and excess water stress

model to respond appropriately over a wide range of soil and weather data at the MAC, lending credibility to the overall simulation exercise.

Seven irrigation management strategies were considered in this study, including ZC-SSIM and three variants each of SC-SSIM and CUIM (Table 2). Each of the 11 parcels were assessed independently. For ZC-SSIM, simulation results were obtained with unique irrigation schedules for each 10 m × 10 m management zone, computed using the strategy described above. For SC-SSIM, the parcels were assumed to be irrigated by machines moving linearly in a north–south direction with laterals extending in the east–west direction. Because no rate changes could occur in the east–west direction with SC-SSIM, irrigation for all management zones in the row were scheduled uniformly based on the conditions of a single zone. Three different cases of SC-SSIM were considered, where irrigation schedules in all zones in a given row were based on the zone with the minimum, median, or maximum AWHC in that row (denoted SC-SSIM-MIN, SC-SSIM-MED, and SC-SSIM-MAX, respectively). Likewise, three cases were considered for CUIM (denoted CUIM-MIN, CUIM-MED, and CUIM-MAX, respectively), where the management zones with the minimum, median, and maximum AWHC were identified across the entire parcel, and the irrigation schedule for those zones was used to simulate all other management zones in the parcel. Typically, small AWHC corresponded to sandier soils with less ability to hold water. Managing for the soil with the smallest AWHC is a common strategy to reduce wastage with CUIM (Daccache et al. 2015). Managing for the soils with median or maximum AWHC provided alternative management scenarios for further intercomparisons of ZC-SSIM, SC-SSIM, and CUIM in this study.

High-performance computing was required, because the irrigation scheduling computations required hundreds of simulations per management zone and year. Simulations were conducted using USDA's high-performance computing resource called Ceres, which consisted of 64 compute nodes each having 40 logical cores on Intel Xeon processors with hyper-threading and a shared 2 PB storage system with Lustre design. Located in Ames, Iowa, access to Ceres occurred via the dedicated high-speed networking resource called SCINet. A Python script that incorporated Python's "multiprocessing" package was developed to manage the simulation tasks using parallel processing on Ceres. The Python script managed the worker processes, loaded geospatial data for each management zone into the model input files, conducted simulations to solve for the irrigation schedule, and retrieved pertinent simulation outputs from the model files.

Data analysis

The CSM-CROPGRO-Cotton simulations quantified seed cotton yield, seasonal irrigation requirement, and seasonal ET for each year, management zone, parcel, and irrigation management scenario. Furthermore, irrigation water use efficiency (IWUE, kg m^{-3}) was calculated from the ratio of seed cotton yield and seasonal irrigation amount, and crop water use efficiency (CWUE, kg m^{-3}) was calculated from the ratio of seed cotton yield and seasonal ET. To characterize profitability of different water management strategies, marginal net return (r_{mn}, \$ ha^{-1}) was calculated similarly to the approach of Paz et al. (1999) and Thorp et al. (2006):

$$r_{\mathrm{mn}} = y_{\mathrm{f}} \times p_{\mathrm{f}} - w \times p_{\mathrm{w}} \quad (1)$$

where y_f is cotton fiber yield (kg ha^{-1}), p_f is the price of cotton fiber (\$ kg^{-1}), w is the volume of irrigation water used (m^3 ha^{-1}), and p_w is the price of water (\$ m^{-3}). Based on the field-measured results of Thorp et al. (2017), cotton

Table 2 Simulated irrigation management strategies for parcels divided into 10 m × 10 m management zones at the Maricopa Agricultural Center, Arizona

Abbreviation	Description
CUIM-MIN	Conventional uniform irrigation management for the entire parcel based on the zone with minimum available water holding capacity
CUIM-MED	Conventional uniform irrigation management for the entire parcel based on the zone with the median available water holding capacity
CUIM-MAX	Conventional uniform irrigation management for the entire parcel based on the zone with maximum available water holding capacity
SC-SSIM-MIN	Speed-controlled site-specific irrigation management based on the zone with minimum available water holding capacity along the lateral
SC-SSIM-MED	Speed-controlled site-specific irrigation management based on the zone with the median available water holding capacity along the lateral
SC-SSIM-MAX	Speed-controlled site-specific irrigation management based on the zone with maximum available water holding capacity along the lateral
ZC-SSIM	Zone-controlled site-specific irrigation management with unique irrigation schedules for all zones

fiber yield was assumed to be 40% of the simulated seed cotton yield, and the mean cotton price over the past 10 years, \$1.7879 kg^{-1}, was used. Any profit due to marketing of cottonseed was not considered in the analysis. The current mean price of Colorado River water purchased from irrigation districts in central Arizona is \$0.0413 m^{-3}. Cotton yield, irrigation volumes, water use efficiencies, and marginal net returns were aggregated at the parcel level on an annual basis for each of the seven irrigation management strategies.

Analyses of variance (ANOVA) and Tukey's multiple comparisons tests were conducted to identify the irrigation management strategies (Table 2) that resulted in statistically different simulation outputs over the long term. Irrigation strategies that were statistically identical to ZC-SSIM were identified, meaning the strategy was able to achieve the same long-term outcome as ZC-SSIM without requiring additional investments in ZC-SSIM technology. The statistical analysis was conducted using the "lme4" and "multcomp" modules of the R Project for Statistical Computing software (www.r-project.org).

Results

Effects on yield

For the majority of parcels, long-term seed cotton yield for the CUIM-MED and SC-SSIM-MED irrigation strategies was statistically grouped with yield for the ZC-SSIM strategy (Table 3). Furthermore, either the CUIM-MAX or SC-SSIM-MAX strategy achieved the maximum seed cotton yield in all parcels. Therefore, adoption of ZC-SSIM offered no long-term yield benefit, because the same or better yield outcomes could be achieved using irrigation strategies that would require less sophisticated technology. If the objective was to maximize long-term yield, the simulations showed that CUIM based on the soil with maximum AWHC was often the best strategy, although it required more water. When using the detailed Thorp soil data for Parcel #6, yield for all strategies was lower than for the Post soil data; however, the statistical groupings were similar for the two soil data sets. Thus, increasing the spatial detail of the soil data did not lead to different conclusions on performance of the CUIM and SSIM strategies.

Minimum seed cotton yield was obtained with the CUIM-MIN for a majority of the parcels and with SC-SSIM-MIN for Parcel #9. The difference between maximum and minimum long-term yield among the tested irrigation strategies ranged from 242 to 615 kg ha^{-1} with percent differences from 4 to 11% (not shown). In efforts to calibrate the model, Thorp et al. (2017) reported root mean squared errors between measured and simulated seed cotton yield up to 12%, so the yield differences in the present simulation exercise are well within the margin of error typically attributed to this model. This means that although relative comparisons among the simulated irrigation scenarios may be informative, the model cannot usually simulate yield measurements with the precision exhibited in the differences among these simulations.

The simulated yield outcomes arise from the relationships among lower limit, potential root water uptake, potential transpiration, and water stress factors in the model. Daily potential root water uptake is calculated as a function of volumetric water content, lower limit, and root growth in each soil layer. If potential root water uptake can satisfy evaporative demand as expressed with potential transpiration,

Table 3 30-year mean seed cotton yield (kg ha^{-1}) for 11 parcels with conventional uniform irrigation management (CUIM) and speed-controlled (SC-) and zone-controlled site-specific irrigation management (ZC-SSIM). Irrigation management for CUIM and SC-SSIM were based on zones with the minimum (MIN), median (MED), and maximum (MAX) available water holding capacity

Parcel	Soil data	CUIM-MIN	CUIM-MED	CUIM-MAX	SC-SSIM-MIN	SC-SSIM-MED	SC-SSIM-MAX	AC-SSIM
1	Post	5177a	**5480**c	*5677e*	5372b	**5459**c	5543d	**5442c**
2	Post	5163a	**5485**b	*5607c*	5211a	**5465**b	5562c	**5441b**
3	Post	5144a	**5415**c	*5632d*	5264b	**5371**c	5608d	**5427c**
4	Post	5121a	**5442**c	5560d	5271b	**5454**c	*5575d*	**5427c**
5	Post	5216a	**5414**b	*5603c*	5255a	**5433**b	5594c	**5421b**
6	Post	5361a	**5414**b	*5618d*	**5390**ab	**5421**b	5551c	**5418b**
6	Thorp	4973a	**5240**c	*5515e*	5084b	**5301**c	5400d	**5276c**
7	Post	5186a	**5425**c	5513d	5298b	**5416**c	*5531d*	**5406c**
8	Post	4979a	5582d	*5594d*	5215b	**5471**c	5569d	**5432c**
9	Post	**5395**ab	**5406**ab	*5627e*	5385a	**5448**c	5559d	**5428bc**
10	Post	5284a	5371b	*5600e*	5351b	**5464**c	5524d	**5435c**
11	Post	5012a	**5465**cd	*5553e*	5216b	**5452**cd	5485d	**5413c**

Parcel #6 was run with two different soil data sets (i.e., Post and Thorp). Yields that were statistically grouped with yield for ZC-SSIM are highlighted in bold, and the maximum yield achieved for each parcel is italicized there is no impact on simulated crop growth for that day. Otherwise, water stress factors are computed as a function of the degree to which potential root water uptake does not meet potential transpiration, and these are used to restrict photosynthesis and crop growth. Although the simulation analyses for CUIM and SC-SSIM were based on zones with minimum, median, and maximum AWHC (Table 2), the soil data for all parcels demonstrated a consistent relationship between AWHC and lower limit (Fig. 4). That is, the zone with minimum, median, and maximum AWHC was often also approximately the zone with minimum, median, and maximum lower limit, respectively. Clayier soils with high AWHC also had greater lower limits, and sandier soils with low AWHC had reduced lower limits. For a dry environment like Arizona, where lower limits have a greater role in plant water stress, it is important to assess how these patterns in soil properties affected the simulations of cotton yield.

As described in the methods, the strategy for initializing the soil water contents aimed to calculate reasonable initial estimates that considered soil variation across parcels. The results of this effort showed that sandier soils tended to be initialized with slightly more available water than clayier soils (Fig. 5). Furthermore, the clayier soils were often initialized to values below their lower limits, while sandier soils were initialized to values above their lower limits. As a result, up to 12 mm more water was available in sandier soils as compared to clayier soils at the start of simulations. Considering over 1000 mm of irrigation is usually required to produce cotton in central Arizona, the impact of these initial differences on the simulation analysis was likely minimal. The initialization strategy suggested that Arizona soils tend to equilibrate near their lower limit following a cotton season, with a tendency for sandier soils to maintain slightly higher plant available water. Although the realism of this result would require further field investigation, the initialization procedure was deemed able to provide reasonable estimates of initial soil water, such that the results of the

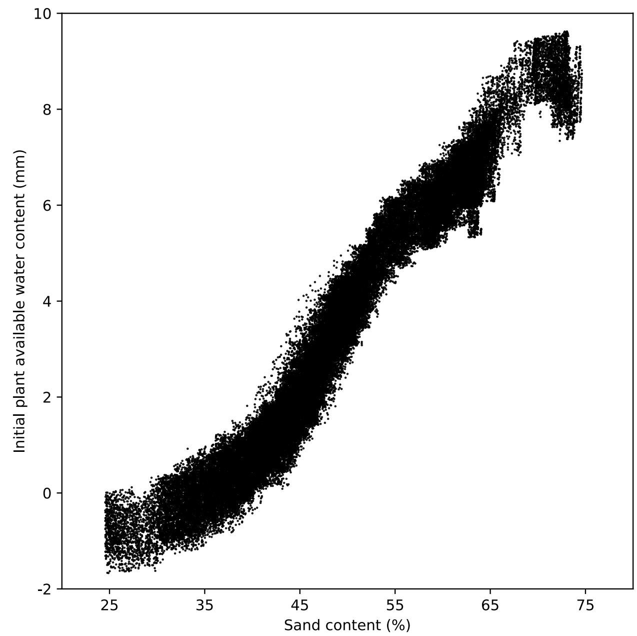

Fig. 5 Initial plant available water (mm) for the upper 120-cm soil profile depth versus sand content (%) from efforts to initialize soil water content site specifically based on data from the 2015 cotton season at Maricopa

simulation study should not be greatly impacted by model initialization settings. The initialization strategy was deemed preferable to other, more preliminary attempts, which initialized the soil water contents by either (1) arbitrarily choosing a value midway between the drained upper limit and lower limit for each soil or (2) fixing the values identically for all soils.

Because one premise of SSIM has been improvement to crop yield, it is somewhat surprising that no ZC-SSIM strategies resulted in higher yield than CUIM-MAX (Table 3). Also, the SC-SSIM-MAX strategy provided minimally higher yield than CUIM-MAX for only two parcels

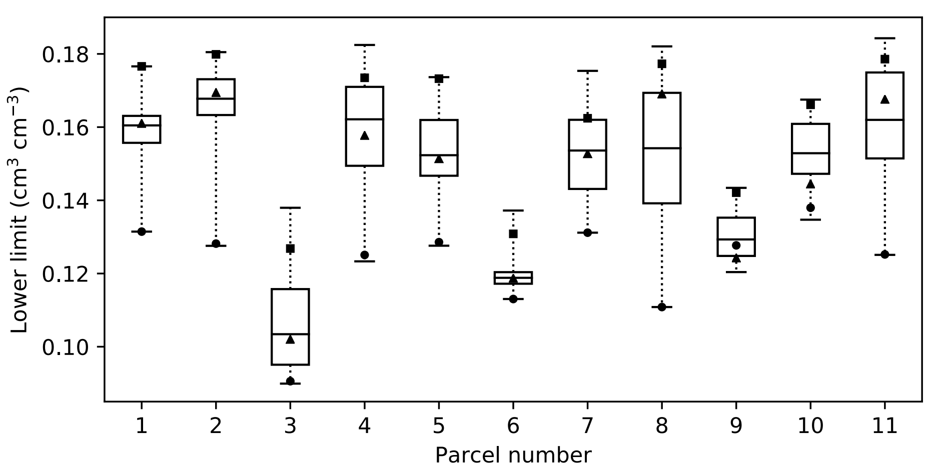

Fig. 4 Box plots of the lower limit among the 10 m × 10 m zones in each of the eleven parcels, based on kriging interpolation of the Post soil data set. The lower limit of zones with minimum, median, and maximum available water holding capacity are denoted with black circles, triangles, and squares, respectively

(Parcels #4 and #7). Managing for the more clayier, maximum AWHC soil (CUIM-MAX) typically led to the highest amounts of irrigation applied to a parcel (Table 4), ranging from 7 to 59 mm more water as compared to managing for the more sandy, minimum AWHC soil (CUIM-MIN). This can be partially attributed to overcoming lower amounts of initial plant available water in the more clayey soils (Fig. 5). However, with only a 12 mm maximum difference in initial plant available water among all soils, the clayey soils clearly also required more in-season irrigation to meet the criteria of the scheduling algorithm. Thus, when using the CUIM-MAX strategy, more water was added to the sandier soils than was added by any other irrigation strategy. This may have allowed these soils to maintain higher soil water content overall and to be productive for a longer period after irrigation termination. This outcome is supported by the results in Fig. 3a, which showed slight increase in simulated yield when up to 10% more irrigation was added to the computed irrigation schedules. As discussed previously, the irrigation scheduling algorithm sought to eliminate water stress in the week following irrigation applications, an approach that mimics typical irrigation scheduling objectives for real fields. The algorithm did not seek to optimize final yield. Thus, irrigation strategies that added extra water above that of the computed irrigation schedule for a given zone tended to slightly increase yield there. Even if the irrigation scheduling algorithm was improved to optimize final yield, the results demonstrating no advantage of SSIM to substantially improve cotton yield in Arizona would likely remain unchanged, because diminishing yield responses to the additional irrigation applications (Fig. 3a) would likely further reduce yield variation among the evaluated irrigation management scenarios.

Effects on irrigation

For all but three parcels, long-term seasonal irrigation requirements for SC-SSIM-MED were statistically grouped with that for ZC-SSIM (Table 4). For half of the parcels, irrigation requirements for CUIM-MED were grouped with ZC-SSIM. Furthermore, minimum irrigation applications among all parcels always occurred with the CUIM-MIN strategy. Therefore, adoption of ZC-SSIM offered no long-term water savings, because the same or better irrigation scheduling outcomes could be achieved using irrigation strategies that would require less sophisticated technology. If the objective was to save water over the long-term, the simulations showed that CUIM based on the soil with minimum AWHC was the best strategy, although it reduced yield (Table 3). The difference between maximum and minimum long-term irrigation requirements among the tested irrigation strategies ranged from 7 to 59 mm year^{-1} with percent differences from 1 to 6% (not shown). When using the detailed Thorp soil data for Parcel #6, irrigation requirements were increased by no more than 6 mm annually for all irrigation strategies. Thus, increasing the spatial detail of the soil data led to less than 1% differences in irrigation amount for this parcel.

Results for long-term seasonal ET (not shown) were similar to that for irrigation requirement. In a majority of zones, CUIM-MED and SC-SSIM-MED led to seasonal ET that was statistically grouped with ZC-SSIM. Furthermore, CUIM-MIN minimized long-term seasonal ET in all parcels. For all irrigation management strategies and parcels, seasonal ET was between 93 and 97% of irrigation applied. As expected for this arid central Arizona

Table 4 30-year mean seasonal irrigation requirement (mm) for 11 parcels with conventional uniform irrigation management (CUIM) and speed-controlled (SC-) and zone-controlled site-specific irrigation management (ZC-SSIM)

Parcel	Soil data	CUIM-MIN	CUIM-MED	CUIM-MAX	SC-SSIM-MIN	SC-SSIM-MED	SC-SSIM-MAX	ZC-SSIM
1	Post	*981*a	**1008**c	1027e	998b	**1007**c	1017d	**1007**c
2	Post	*985*a	1018d	1029f	990b	**1017**cd	1026e	**1015**c
3	Post	*960*a	968b	989e	962a	967d	983d	**971**c
4	Post	*981*a	**1013**c	1029e	994b	**1012**c	1026d	**1011**c
5	Post	*988*a	**1006**	1029e	991b	**1005**c	1026d	**1007**c
6	Post	*977*a	**979**bc	988e	978ab	**980**bc	985d	**980**c
6	Thorp	*982*a	**984**b	989c	**984**b	**986**b	**986**b	**985**c
7	Post	*987*a	**1010**c	1023e	999b	**1009**c	1019d	**1009**c
8	Post	*970*a	1012d	1029f	985b	**1006**c	1021e	**1004**c
9	Post	*981*a	983b	997e	982a	**985**c	990d	**985**c
10	Post	*988*a	998c	1020g	995b	1006e	1010f	**1004**d
11	Post	*981*a	1021d	1035f	998b	1020d	1024e	**1017**c

Irrigation management for CUIM and SC-SSIM were based on zones with the minimum (MIN), median (MED), and maximum (MAX) available water holding capacity. Parcel #6 was run with two different soil data sets (i.e., Post and Thorp). Irrigation amounts that were statistically grouped with amounts for ZC-SSIM are highlighted in bold, and the minimum irrigation requirement achieved for each parcel is italicized agroecosystem, a majority of water loss was simulated through the ET pathway, leading to limited opportunity for improving efficiency through reduction of water losses in runoff and drainage.

For all but one parcel, the long-term irrigation water use efficiency (not shown) for CUIM-MED, SC-SSIM-MED, and ZC-SSIM was grouped statistically. Additionally, the long-term crop water use efficiency (not shown) for ZC-SSIM was statistically grouped with CUIM-MED and SC-SSIM-MED for all but two parcels. Furthermore, CUIM-MAX maximized both irrigation water use efficiency and crop water use efficiency in a majority of the parcels. Therefore, the simulations demonstrated little advantage for SSIM to improve water use efficiency among these parcels, because CUIM could achieve the same or better outcomes over the long term.

Effects on net return

As expected, results for long-term marginal net return were similar to that for seed cotton yield and irrigation requirements. For all the parcels, the long-term marginal net return for SC-SSIM-MED was statistically grouped with that for ZC-SSIM (Table 5). For all but two parcels, marginal net return for CUIM-MED was grouped with ZC-SSIM. Similar to results for yield, maximum marginal net return was achieved with CUIM-MAX in all but two parcels, and SC-SSIM-MAX maximized marginal net return in the remaining two parcels. Therefore, adoption of ZC-SSIM offered no long-term improvement in marginal net return, because the same or better outcomes could be achieved using irrigation strategies that would require less sophisticated technology.

Changes in the price of cotton fiber or water will likely not impact the outcomes of this study concerning SSIM technology. Variation in long-term yield among the tested irrigation scenarios (Table 2) was often twice the amount of variation in long-term irrigation requirement (Fig. 6). Thus, the management scenarios led to much greater opportunity to affect marginal net return through changes in yield rather than changes in applied irrigation. Furthermore, returns from selling cotton fiber ($\$\,ha^{-1}$) are currently eight times higher than expenditures for water purchases. From an economic perspective, the value of the fiber is much greater than the value of the water. If the price of cotton fiber substantially increased, more funds would be available to invest in water management technologies, although this study has demonstrated few opportunities for SSIM to improve yield or save water. If cotton prices decreased or water prices increased, less funds would be available for investment in new technology, which would hinder adoption. Finally, given the state of water politics in Arizona, water prices will likely not decrease in the future. In fact, the threat of reduced allocations of Colorado River water to central Arizona agriculture is currently a more dire concern than the price of water.

Discussion

A main strength of simulation studies is the ability to assess agronomic outcomes of different management options over many years and spatial locations, providing results that would be impractical to achieve by field experimentation. However, models can only imperfectly simulate the processes occurring in an agroecosystem, and several limiting assumptions of this study require further clarification.

Table 5 30-year mean marginal net return ($\$\,ha^{-1}$) for 11 parcels with conventional uniform irrigation management (CUIM) and speed-controlled (SC-) and zone-controlled site-specific irrigation management (ZC-SSIM)

Parcel	Soil data	CUIM-MIN	CUIM-MED	CUIM-MAX	SC-SSIM-MIN	SC-SSIM-MED	SC-SSIM-MAX	ZC-SSIM
1	Post	3297a	**3502**c	*3636*e	3429b	**3488**c	3543d	**3476**c
2	Post	3285a	**3502**b	*3585*c	3317a	**3488**b	3553c	**3471**b
3	Post	3282a	**3473**c	*3619*d	3367b	**3442**c	3604d	**3480**c
4	Post	3257a	**3474**c	3551d	3359b	**3482**c	*3563*d	**3463**c
5	Post	3322a	**3456**b	*3582*c	3348a	**3470**b	3577c	**3461**b
6	Post	3430a	**3467**b	*3610*d	**3450**ab	**3472**b	3562c	**3470**b
6	Thorp	3150a	**3341**c	*3536*e	3229b	**3384**c	3455d	**3366**c
7	Post	3301a	**3463**c	3520d	3376b	**3456**c	*3534*d	**3449**c
8	Post	3160a	3573d	*3575*d	3323b	**3497**c	3560d	**3469**c
9	Post	**3453**ab	**3460**ab	*3612*e	3445a	**3489**c	3566d	**3475**bc
10	Post	3370a	3429b	*3584*e	3416b	**3492**c	3533d	**3472**c
11	Post	3179a	**3486**cd	*3544*e	3318b	**3478**cd	3500d	**3451**c

Irrigation management for CUIM and SC-SSIM were based on zones with the minimum (MIN), median (MED), and maximum (MAX) available water holding capacity. Parcel #6 was run with two different soil data sets (i.e., Post and Thorp). Marginal net returns that were statistically grouped with returns for ZC-SSIM are highlighted in bold, and the maximum marginal net return achieved for each parcel is italicized

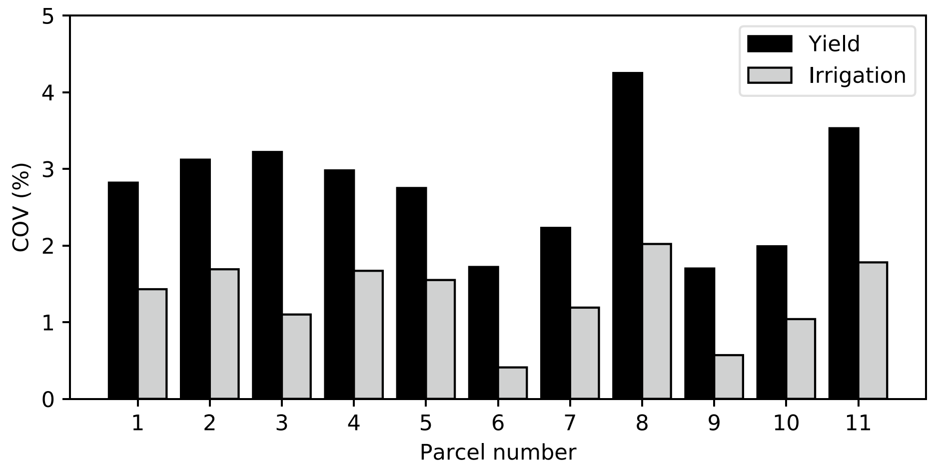

Fig. 6 Coefficient of variation (COV) for cotton fiber yield and irrigation requirements among the evaluated irrigation management scenarios in each of the eleven parcels

Foremost, although many factors contribute to field variation, the simulations herein were limited mainly to the effects of soil texture variability across parcels. Furthermore, uncertainty in soil sampling protocols, soil texture analysis procedures, and computations of pedotransfer functions likely contributed to uncertainty in simulation outcomes. Due to such limitations, further evaluations of SSIM in field or simulation settings for other environments, crops, or soils are certainly warranted. The conditions of other agroecosystems may lead to different conclusions regarding SSIM. For example, this study does not account for differences in field topography, mainly because laser-leveling practices in central Arizona have made topography irrelevant. In other regions where topographic variability combined with higher precipitation amounts lead to greater potential for overland flow, lateral seepage, and spatial variability in soil water contents, SSIM technology may provide greater advantages, and models capable of simulating these processes may be necessary to demonstrate the benefit. Factors other than water, many of which are not simulated by agroecosystem models, may also lead to variable water requirements across a field. Potentially, SSIM could be useful for reducing water applications to areas experiencing nutrient deficits, pest infestations, poor emergence, and other spatially variable factors that were not simulated in this study. Further studies that integrate in-field data from plant and soil sensors into spatial model simulations may provide improved insights on the need for SSIM to address in-field variability. However, the results of the present simulation study clearly challenge the notion that SSIM is beneficial for improving water management in central Arizona cotton production, where extremely limited precipitation, level topography, and negligible overland flow reduce potential for spatial soil water variability.

Understanding the reasons for the results can provide rich guidance for future efforts to improve irrigation management. First, the study assumed that scientific irrigation scheduling technologies were implemented prior to considering SSIM. Irrigation schedules for CUIM were computed using the same algorithm as for SSIM. The only difference was how the schedules were spatially applied, which depended on the style of irrigation machine assumed and the particular soil chosen for management. Thus, the simulation results demonstrate effects of spatial irrigation management independent from irrigation scheduling, showing little advantage for the former. This distinction should be the focus of future studies on SSIM. Specifically, the ability of irrigation technologies to improve spatial irrigation management must be evaluated independently from their ability to improve irrigation scheduling decisions. This way, the added value of technologies for spatial application of water can be identified. Obviously, efforts should be focused on the technologies that offer the greatest impact toward improving irrigation management as a whole, regardless of whether irrigation is administered on a geospatial basis or not. This likely means first developing technologies to optimize CUIM given site-specific information on soil and plant variability, followed by consideration of whether SSIM can make further improvements. Technologies required for improving CUIM will likely also be required for SSIM, while not all technologies required for SSIM are necessarily required for CUIM. Thus, efficiency and simplicity can be gained if SSIM is demonstrated not to offer benefits.

The model simulations generally showed opposing outcomes using CUIM for the extreme soil properties. The CUIM-MIN and CUIM-MAX scenarios essentially represented the "end member" management conditions for each parcel. If a grower was using CUIM for the sandy soil with minimum AWHC (CUIM-MIN), generally the least water was used but yield was also minimized. On the other hand, if a grower was using CUIM for the clayey soil with maximum AWHC (CUIM-MAX), generally the yield was maximized, but a lot of water was required. Results for other management options, including SSIM approaches and CUIM for the soil with median AWHC (CUIM-MED), generally demonstrated yield and irrigation requirements between the extreme cases. The problem for SSIM was that the differences between the end member cases were relatively small: less than 11% for yield and less than 6% for irrigation applied. This means differences in yield or applied irrigation for SSIM as compared to CUIM-MED were even smaller, making SSIM technology difficult to justify. Ability to update model simulations using in-season spatial soil water content or plant growth measurements may demonstrate greater advantages for SSIM. Spatial regions where field data disagreed with simulated data could challenge modeling assumptions and identify spatial processes that models do not simulate well.

A primary reason for the overall low variability in simulated outcomes (Fig. 6) was related to the scheduling of irrigation events on a weekly basis. Although somewhat arbitrary, the decision to irrigate weekly was based on a practical scheduling methodology that had been field tested for several growing seasons (Thorp et al. 2017) and was shown to work conveniently with the labor and water delivery constraints for conducting irrigation at the MAC. However, with weekly irrigation management, the AWHCs of most MAC soils are more than sufficient for CUIM. Among all the 10 m × 10 m zones in all parcels, the minimum, median, and maximum AWHC's were 0.098, 0.131, and 0.162 $cm^3\ cm^{-3}$, respectively. Assuming a typical fully grown Arizona cotton canopy with root growth to 1.5 m and assuming that soil water content less than 50% of AWHC is undesirable, the minimum, median, and maximum AWHC levels equate to 74, 98, and 122 mm of useful water, respectively, when the soil profile is full. Peak ET demands during an Arizona cotton season typically occur in early July, requiring 10–12 mm of water per day or 70–84 mm of water per week. In other times of the season, ET demands are much less. Thus, at most times during the season, most soils at the MAC have more than enough AWHC to sustain cotton production at maximum growth rates for a week or more. This means soil water can generally be replenished on a weekly basis using CUIM with little threat of plant water stress and little need for SSIM. If the interval between irrigation events was longer than 1 week, more crop growth variability may result from water retention differences among soils, leading to differential water stress conditions. However, according to the simulations, this problem can be eliminated for Arizona cotton simply by irrigating more frequently using CUIM. Likewise, for other regions, the frequency of irrigation events as compared to the range of AWHC and level of water demand will likely influence the value of SSIM as compared to CUIM.

To generalize these findings for other regions, the minimum time scale for irrigation management must first be considered, which is equal to the time that the minimum AWHC soil can supply water at peak crop water demand (e.g., conveniently about seven days for central Arizona cotton). For other regions, this time may be higher or lower, depending on the relationships between AWHC and peak water demand. For example, very sandy soils may only have enough capacity to sustain plant growth for a couple days at peak water demand, necessitating more frequent CUIM to meet demand. Assuming the capacity of the irrigation system is sufficient to apply the water requirement within the minimum time interval, SSIM will likely offer no agronomic benefit, because CUIM can be used within the time interval to meet the water requirement without overshooting the capacity of the lowest AWHC soil. If the capacity of the irrigation system is not sufficient for this task, investments to increase the irrigation system capacity should likely supersede investments in SSIM. Otherwise, plant stress may be unavoidable due to limits of the irrigation system itself. It follows that SSIM may be worthwhile only if, for whatever reason, the irrigation applications must occur at an interval larger than that defined by the supply of the minimum AWHC soil. If irrigation system capacity allowed it, SSIM could then be used to apply more irrigation to the higher AWHC soils while reducing irrigation to eliminate wastage due to overshooting the capacity of the lower AWHC soils. For example, if the time interval for depleting the minimum AWHC soil was very short, the required frequency of CUIM may be too often or too impractical, lending an opportunity for SSIM. As the irrigation management time scale becomes more infrequent such that CUIM cannot meet water requirements without wastage in the minimum AWHC soils, SSIM may become more useful to account for variability in soil water holding characteristics. On the other hand, investments in SSIM technology cannot be justified when optimizing the frequency of CUIM is a valid solution.

This study assumed that sufficient water supplies were available for irrigation management, which is becoming more unrealistic for central Arizona and is already unrealistic for many other irrigated regions in the world. Preliminary simulations for the present study sought to consider the impact of limited water supplies as related to SSIM versus CUIM. Two extreme cases were tested to meet water supply restrictions at the parcel level: (1) a SSIM case where irrigation was iteratively excluded from the management zones that exhibited lowest IWUE until the water restriction was met and (2) a CUIM case where the daily irrigation amounts over the entire growing season were reduced by the fraction necessary to meet the restriction. As compared to deficit irrigating the entire parcel with CUIM (Case #2), these preliminary results (not shown) consistently demonstrated that higher yield and IWUE was possible at the parcel level by applying full irrigation to the spatial zones with highest water use efficiency and ceasing irrigation on other areas of the field (Case #1). These results were not presented due to the extreme and somewhat unrealistic nature of the tested cases. Particularly for Arizona cotton, completely eliminating irrigation over any land area will terminate production there, because rainfall is inadequate. This may not be the case for other regions, where precipitation may be plentiful enough for rainfed production, making SSIM a possibility for allocating limited water supplies to the most beneficial areas. Furthermore, simply reducing the full irrigation schedule by a constant fraction is likely not a realistic approach for using CUIM to meet water supply restrictions. Instead, the results suggest that better algorithms are needed to optimize irrigation schedules for cases when water supply is limiting, a task that will be left to future research. Nonetheless, results of this preliminary test suggested that spatial management of full irrigation was a better alternative than whole-field deficit irrigation to meet water restrictions for Arizona cotton production.

Agroecosystem models are useful tools for evaluating irrigation management options; however, algorithms for computing irrigation schedules that optimize productivity or other agroecosystem metrics are lacking. For example, in the present study, models were used simply to determine the irrigation rate that met ET requirements and eliminated water stress in the coming week, a strategy that is commonly used to schedule irrigation for real fields. Alternatively, algorithms are needed to calculate irrigation schedules while considering final yield outcomes or restrictions for seasonal water availability. The latter is a much more computationally complex optimization problem, and adding the spatial dimension complicates it even further. With better algorithms for optimizing irrigation schedules to achieve specific outcomes for yield and seasonal irrigation limits, the analysis presented herein could be repeated to gauge potential benefits for SSIM under limited water scenarios. In particular, SC-SSIM may demonstrate value in this case, while ZC-SSIM may be impractical because of the higher capital investment required.

A novel geospatial strategy resulted from this work, which involved the division of parcels into $10\,\text{m} \times 10\,\text{m}$ zones with independent calculation of irrigation schedules for each one. Clearly, this task was required for assessment of SSIM. However, the technique also permitted testing CUIM outcomes by simulating all zones using the irrigation schedule computed for a single zone. In addition to allowing direct comparisons of CUIM and SSIM, the approach highlighted how geospatial data could be used not only to inform management decisions for SSIM but also for CUIM. For example, the results for CUIM differed depending on which zone was used for scheduling. Even if an irrigation system is not equipped with the technology required for SSIM, geospatial data can still be useful and informative for optimizing CUIM.

Conclusions

Although SSIM remains a promising technology for applications in precision irrigation, this simulation analysis demonstrated no benefit of using SSIM for cotton production in central Arizona, assuming sufficient water supplies for full irrigation. Fiber yield and marginal net return could be maximized using a strategy for CUIM, and irrigation requirements could be minimized using a different CUIM strategy. Strategies for CUIM often provided statistically similar results as compared to SSIM over the long term. Future research should focus on technologies for optimizing temporal scheduling of CUIM, particularly under limited water scenarios. Assessments of SSIM technology may provide different results for other crops and environments or for conditions of reduced water availability.

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